HESSISCHE STIFTUNG
FRIEDENS- UND KONFLIKTFORSCHUNG

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SDI for Europe?

Technical Aspects of Anti-Tactical Ballistic Missile Defenses

PRIF Research Report 3/1988

Frankfurt am Main

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Acknowledgements

This research project was done while I was a research assistant at the Peace Research Institute Frankfurt; it was funded by a grant from the Stiftung Volkswagenwerk.

During the two years of the project I had the opportunity to work for four weeks at the Center for International Security and Arms Control, Stanford University; I thank Benoit Morel (now at Pittsburgh) and especially Ted Postol for their hints on literature and for their many helpful discussions. Thanks go also to John Pike of the Federation of American Scientists, Washington, for letting me use his files.

For critical comments on the manuscript I thank the following colleagues: Lilo Altmann, Gert Krell, Bernd Kubbig, Uwe Reichert, Thomas Risse-Kappen and Hans-Joachim Schmidt.

My English was smoothed by Leslie Booth and Desiree Kelly.

Bochum/Frankfurt, September 1988 Jürgen Altmann

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ISBN 3 – 926197 – 49 – 8

Summary

Over the last years, plans for West European defenses against Soviet tactical ballistic missiles have emerged. One reason for this is the technical developments in the field of air defense. The other, more important reason is the U.S. SDI project. Whereas SDI proponents emphasize defense against nuclear missiles and the connection to the U.S. project, the West German government gives non-nuclear missiles as the main argument; in its view, a more modest "extended air defense" separated from SDI is required. First steps are being made to provide modern air defense missiles with some capability against short-range ballistic missiles. Within SDI ground-based interceptors planned for use against strategic ballistic missiles are first tested against short-range missiles.

Properties of Tactical Ballistic Missiles

Tactical ballistic missiles comprise a large span from 60 km range (akin to artillery rockets) to 5,500 km range (resembling intercontinental ballistic missiles). Having high velocities (1 to 5 km/s), they arrive at a target much faster than aerodynamic missiles or aircraft; flight times vary between 2 and 30 minutes, according to the range. Ballistic missiles of shorter ranges do not leave the atmosphere; above about 500 km range, a significant portion of the flight duration is spent in space.

Unlike strategic missiles, most present tactical ballistic missiles have only one warhead. Most tactical ballistic missiles are launched from mobile vehicles.

Up to now, almost all tactical ballistic missiles are guided by inertial measurement. This provides for a targeting accuracy (circular error probable) of several hundred meters. Therefore, nuclear warheads must be used to produce significant military damages. Even if inertial guidance could be improved to circular errors probable of less than 100 m, efficient use of conventional warheads on tactical ballistic missiles would require marked increases in accuracy which can only be provided by some form of target recognition and terminal guidance.

Technologies of Anti-Tactical Ballistic Missile Systems

Technologies which can be used for anti-tactical ballistic missile defense vary with the missile range, and with the time scale foreseen for their deployment. Ballistic missiles with the shortest ranges could be attacked by modified air defense systems, whereas for missiles with longer ranges systems developed for defense against strategic missiles are appropriate. Deployment could begin with fast ground-based interceptors, later augmented by air- and spaceborne sensors. In a couple of years, the use of space-based interceptor projectiles could follow. Deployment of a space-based beam weapon defense systems is in the distant future.

Early deployable anti-tactical ballistic missile defenses would be based on mobile radars and interceptors. Due to the limited radar search range, these would attack incoming warheads in

the atmosphere, providing some defense capability against present tactical ballistic missiles of up to 1,000 km range.

Long-wave infrared sensors carried on board high-flying aircraft are in principle capable of detecting ballistic missiles or their reentry vehicles in space at ranges of up to 1,000 km. The same would hold for long-wave infrared sensors "popped up" on rockets launched on warning of attack, and on sensors permanently deployed on board low-flying satellites. Such sensors are required if exoatmospheric interception in the midcourse phase is to be attempted. Short-wave infrared detection of missile exhaust flames is possible from satellites even in geostationary altitudes for all but the shortest ranges.

Exoatmospheric interceptors could be deployed on the ground or on board satellites. In the former case, interceptor missiles would hit their targets at several hundred kilometers distance from their launch points, far beyond the border or front. If they continued their trajectory, they could hit targets deep inside the other's territory. If space-based interceptors are to be present in sufficiently high numbers in a region where tactical ballistic missiles could be used, ten thousands of projectiles would have to be deployed globally on several hundreds up to several thousands of satellites.

Beam weapons deployed in space (or having some components like relay mirrors in space) are far away from a status where they could contribute in a significant way to a ballistic missile defense.

In the traditional systems for defense against strategic ballistic missiles, nuclear explosions were used as intercepting weapons. If defense against nuclear ballistic missiles is a goal, the defense must try to prevent salvage-fused warheads from exploding and creating an access to the target for follow-up warheads. This produces a tendency to use nuclear warheads on the interceptors. If the nuclear-explosion pumped x-ray laser proves feasible and is fully developed, such nuclear warheads could also be deployed in Europe for exoatmospheric intercept.

Non-nuclear interception can be done with conventional explosive charges surrounded by shrapnel-forming metal; this principle is foreseen for interception in the atmosphere. It requires guidance to some 5 meter distance from the incoming warhead. Outside the atmosphere, direct hits can be achieved by infrared sensor guidance; depending on the existence of unfolded structures, miss distances between 0.3 and 5 m are necessary.

Expected Efficiency of Anti-Tactical Ballistic Missile Defenses

Anti-tactical ballistic missile defense is much more akin to defense against strategic missiles than it is to air defense, except perhaps for the shortest ranges of 100 or 200 km. Because ballistic missiles are harder to detect and hit than aircraft, defense efficiencies are unlikely to exceed those of air defense systems (i.e., will remain at less than 10% for a massive attack).

Similarly to the case of strategic missiles, there exists a number of countermeasures which could be used to ensure penetration through anti-tactical ballistic missile systems. Some (like light-weight decoys) could not be used with the shortest ranges, but others could prove very effective. These include: reducing the radar reflex of reentry vehicles; increasing the missile numbers; lofting or depressing of trajectories; introducing multiple nuclear warheads; salvage fusing of nuclear warheads; maneuvering reentry vehicles; earlier release of submunitions; new types of decoys; electronic or electro-optical countermeasures. Offensive countermeasures could be: attacking search radars with radiation-seeking missiles; attacking sensor-carrying aircraft with long-range interceptor missiles; attacking satellite-based sensors or weapons with ground- or satellite-based interceptors.

As in the case of strategic ballistic missiles, and even more so, there is no chance of protecting the population from attack with tactical ballistic missiles equipped with nuclear warheads. For nuclear attacks against military targets in Europe, defenses make less sense than for attacks against superhardened strategic missile silos (where a great portion could be sacrificed without significantly reducing the second-strike potential of the missile force as a whole).

Against conventionally equipped tactical ballistic missiles, defenses can achieve a limited capability; the difficulties increase with the missile velocity (and thus the range). Because conventional ballistic missiles are not a significant threat, however, this limited performance level is without great relevance.

Strategic Stability with Anti-Tactical Ballistic Missile Systems

Strictly local, and limited, anti-tactical ballistic missile defense systems could in theory be built without adverse effects on strategic stability. Because there is not a significant threat from conventional ballistic missiles, they are in any case not needed to reverse a destabilizing trend.

The more ambitious the goals of defense become, the higher and and further out the intercepting weapons reach, the more ambiguities arise. On the one hand, systems that could be used offensively, or that could not reliably be discriminated from others capable of offensive uses, create threats and threat perceptions which will lead to increased arms build-up. On the other hand, if such systems have to be launched on short notice, they will in a crisis situation increase the nervousness, and the chances that misunderstandings or unclear events could lead to war.

Some anti-tactical ballistic missile techniques could indeed be used offensively. If nuclear interception warheads were used, they could be alternatively directed at ground targets. Interceptor missiles for attacking ballistic missiles at greater altitudes and ranges could in principle be used to attack command and control as well as sensor-carrying aircraft flying in rear areas. Any interceptor for exoatmospheric interception of ballistic missiles is inherently better suited to destroy satellites at similar altitudes. This affects low-orbit satellites for reconnaissance, but also those which are foreseen for search and tracking of ballistic reentry vehicles, and for carrying space-based interceptors.

Ambiguities can arise, because interceptor missiles cannot under all circumstances be recognized as defensive. If in a crisis, an interceptor was launched because of a mistake, or because of an object erroneously entering one's air space, this could spell crossing the threshold from crisis to war. Specific problems are also created by infrared sensors on pop-up rockets. By definition, they have to be launched on warning, i.e. on indications of an attack. Only if they were launched from fairly rear positions, and at trajectories not leading towards the border, could misunderstandings as offensive ballistic missiles be avoided.

Any kind of anti-tactical ballistic missile defense has to react very quickly. If an incoming re-entry vehicle is detected by a local radar, delaying an interceptor launch decision by 15 or 30 seconds can mean that the warhead hits its target unimpeded. There may be time for human intervention at the operator level, but certainly not on the political level. Creation of central NATO or WTO commands for anti-tactical ballistic missile defense could prevent local operators from triggering a war out of local unclear events. On the other hand, they would bear new risks of errors on a larger scale, and political control would likewise be impossible in less than a one minute decision time.

The greatest danger for crisis stability is to be feared if both sides command space weapons. Mutual attacks could be brought forward within seconds with kinetic energy weapons, and within split seconds for beam weapons. The need for automated decisions and the possibility that a first attacker would end up with a significant advantage, will create high preemption instability.

Because of the limited efficiency of anti-tactical ballistic missile defenses, it is likely that they will be supplemented by offensive strikes at the launchers before the (second or even first) missile is launched – such strikes are in fact elements of many plans and recommendations how to deal with the "new conventional ballistic missile threat". Of course, real-time reconnaissance of mobile launchers deep inside the other's territory is very difficult, and can be made even more so by camouflage and other countermeasures. A hypothetical situation in which both sides had achieved this reconnaissance, and could effectively knock out each other's ballistic missile launchers using their conventional ballistic missiles, i.e., within 5 or 10 minutes, would be very destabilizing in a crisis. Because of worst-case thinking, this effect may occur even if it has little basis in reality.

Anti-Tactical Ballistic Missile Defense and Arms Control

Because there is overlap in range and trajectory with some submarine-based strategic ballistic missiles, defense against tactical ballistic missiles of more than about 2,000 km range is neither allowed for the USA nor the USSR under the ABM Treaty, and such technology may not be transferred to other countries. Any system or component of anti-tactical ballistic missile systems of these two states which is air- or space-based and could also be used against strategic ballistic missiles, is not allowed under the treaty. In order to prevent ambiguities, both countries could agree to limit defense tests against tactical ballistic missiles to ranges below some limit, e.g. 1,000 km.

In order to include other European countries which possess ballistic missiles, and could build defense systems against them, a more general solution seems advisable. The INF Treaty has removed many reasons for defenses against tactical ballistic missiles above 500 km range. A more stringent limit appropriate for dividing defense against aerodynamic missiles from defense against most types of tactical ballistic missiles is at about 200 km ballistic range. In order to ensure an unambiguous and long-lasting ban on defense against ballistic missiles above that range, NATO and WTO countries should ban defenses, including development and tests, against objects which at any point of their trajectory had an altitude above 40 km or a velocity above 1.5 km/s. To keep such a ban viable, reductions of existing ballistic missiles above 200 km range should follow.

Smaller European states should try to influence the USA and the USSR to incorporate limits on anti-tactical ballistic missile defense into the ABM Treaty, and should work towards a general treaty more stringently limiting ballistic missiles and defenses against them. In order to back their efforts, these states should clearly obey the limits in their own research and development for modernized defenses against aircraft and aerodynamic missiles.

A reduction of tactical ballistic missiles above 200 km range and a renunciation of defenses against such missiles in Europe will only remain viable over the long run if the quest of third world countries for ballistic missiles is reversed and stopped. First measures taken against proliferation of ballistic missiles should be joined by more countries, and should be made comprehensive and juridically binding in a manner similar to the nuclear Non-Proliferation Treaty.

Table of Contents

1. Purpose and Scope of this Study

After some introductory remarks, the purpose of the present study is given in 1.1. Section 1.2 gives an overview over the different chapters. Important categories used in this work, and limits of its scope, are defined in 1.3.

1.1 Introduction; Purpose of the Present Study

Following the U.S. Strategic Defense Initiative (SDI) program, ideas arose in several quarters about erecting defenses against Soviet tactical ballistic missiles targeted at Western Europe. The U.S. project is directed against long-range nuclear ballistic missiles. Many SDI proponents in the USA and in Western Europe analogously want defenses against nuclear ballistic missiles of tactical ranges. They foresee European defenses with air and space components, directly linked to SDI systems. Some use the name "European Defense Initiative" to designate a similarly comprehensive scope like the U.S. program. The West German Government, on the other hand, has emphasized the threat posed by the conventional tactical ballistic missiles, and not by the nuclear ones. The Government avoids the notions "nuclear" and "space". It has coined the name "Extended Air Defense" for an effort which starts by upgrading the existing air defense systems to a capability against aerodynamic and some shorter-range non-nuclear ballistic missiles.

In the meantime, the Treaty between the USA and the USSR on the Elimination of their Intermediate-Range and Shorter-Range Missiles (INF Treaty) has introduced another, fundamentally different, possibility of dealing with missile threats (nuclear and non-nuclear ones), namely by reducing and dismantling weapons in a mutually controlled way. The abolition of all U.S. and Soviet ground-based missiles with ranges between 500 and 5,500 km can remove many motives for developing and deploying defense systems against tactical ballistic missiles. The treaty has not as yet, however, been followed by agreed limits on research, development and testing of ground- and space-based defense systems against strategic ballistic missiles. These activities continue (and will at some time come into direct conflict with the ABM Treaty). Because of the direct overlap of defense technologies against strategic and tactical ballistic missiles, continuing work in one field will provide incentives for the other. The INF Treaty itself leaves out missiles of less than 500 km range. Compensatory armament by ballistic missiles of such ranges, which is already actively planned for, will increase threats and threat perceptions, creating a second set of motives for anti-tactical ballistic missile defenses.

In addition, there are nuclear ballistic missiles of ranges below 5,500 km of other countries (China, France, Great Britain) which are not affected by the INF Treaty, and are currently not included in any arms reduction talks. Sea-launched ballistic missiles of the USA and the USSR are not subject to the treaty. Other countries are beginning to develop and deploy their own tactical ballistic missiles. If active steps are not taken to contain and eventually reverse these developments, threats and threat perceptions will increase and pressures for defense deployment will rise.

A third group of problems arises out of the tendency for increased military use of aerodynamic missiles for deep-strike purposes. If this continues unchecked, it is inevitable that air defenses will be upgraded to include a capability against aerodynamic missiles. In principle it is possible to do this without creating ambiguities as to defense against ballistic missiles (at least those with ranges above 200 km). If no limits for such activities are introduced, however, the political-military desire for more capable systems will probably, over time, blur the distinction between defense against aerodynamic missiles and defense against ballistic missiles.

The present study undertakes a scientific and technical analysis of anti-tactical ballistic missile systems with a view to strategic stability and arms control. The main questions it tries to answer are:

- What are the characteristics of tactical ballistic missiles?
- What kinds of anti-tactical ballistic missile defenses are possible and how would they work?
- What degree of efficiency can be expected of such defenses (against nuclear as well as non-nuclear ballistic missiles)?
- How would anti-tactical ballistic missile defenses affect strategic stability (concerning the arms race as well as in a crisis)?
- If the net effect on stability is negative, how can limitations for anti-tactical ballistic missile systems be devised that do not unduly impede defense efforts leading to more stability, and are adequately verifiable?

The technical analyses of the report mainly address scientists and engineers. Formulae and basic relations as well as literature references are presented in order to give technical insights to those who are not active in research and development of radar systems, infrared sensors, interceptors etc., but who want to examine the issues independently. No secret information has been used. The goal of this report is to provide a basis for understanding – and critically evaluating – arguments brought forward in the public debate.

The results of these analyses, and the discussion about strategic stability and arms control, are intended to provide information to help also the non-technical reader come to an educated decision on the question of anti-tactical ballistic missile defense.

1.2 Overview over the Study

Chapter 2 gives a short account of the different origins of the present upsurge of concepts for defense against tactical ballistic missiles.

Characteristics of tactical ballistic missiles are presented in *Chapter 3*. Their trajectories and destructive effects are described; a list of deployed and planned missile types follows.

Chapter 4 deals with the technical aspects of different systems and components which can be used for anti-tactical ballistic missile defense. Beginning with techniques for search, after a short look on guidance, the interception mechanisms are analyzed. A list of defense systems and components which are in the development process concludes the chapter.

Systems aspects are treated in *Chapter 5*. Footprint areas of typical ground-based anti-tactical ballistic missile systems are calculated, and properties of space-based kinetic energy weapons are looked at. Further, possibilities of preferential defense and reaction times are discussed.

In *Chapter 6*, possible countermeasures against anti-tactical ballistic missile systems are discussed, and the defense efficiency which can be expected is estimated.

After looking into several possibilities for offensive uses of anti-tactical ballistic missile defenses, and the necessity for short reaction times, prospects for strategic stability after deployment of different types of such defenses are the subject of *Chapter 7*.

Chapter 8 deals with the question how anti-tactical ballistic missile defense relates to existing arms control treaties, especially the ABM Treaty. Then, limits for defense activities are derived which would allow to separate defense against aircraft and aerodynamic missiles from defense against ballistic missiles in an adequately verifiable way.

1.3 Definition of Terms, Limits of Scope

A *missile* is an unmanned air or space vehicle used for carrying destructive effects to a distant target, usually propelled by some form of gas exhaust. Missiles can travel through air space, making use of lift forces acting at the body and wings, and taking in air as oxidant for the fuel; these *aerodynamic missiles* are limited to altitudes lower than about 25 km, they appear above the horizon of a target only late, and often fly at very low altitudes during the approach to the target. Because aerodynamic drag has to be overcome, powered flight is necessary over most of the flight path. Velocities are lower than the velocity of sound (0.34 km/s) at low altitudes, and may reach Mach 3 (1 km/s) at high altitudes. Examples of aerodynamic missiles include anti-aircraft missiles, stand-off missiles, and cruise missiles.

Missiles which leave the atmosphere and/or do not make use of aerodynamic lift to compensate for their weight force for a significant part of their trajectory are called *ballistic missiles*. They are accelerated for a relatively short time by a rocket motor which provides its own oxidizer to a high velocity (from 1 to 7 km/s) in a direction pointing upward at some angle. Subsequently, propulsion stops and they move (like a stone thrown upward) under the influence of the earth gravity (and of the air, where it exists). The direction and magnitude of the velocity at burnout (and, to some extent, the burnout altitude) determine the distance at which the ballistic missile (or its payload) will impact. Distances range from 15 km for artillery rockets which never leave the atmosphere to 13,000 km for intercontinental ballistic missiles which travel 35 out of 38 minutes through space. As long as ballistic missiles are within the lower atmosphere, they can make use of aerodynamic forces as well (to compensate for the weight force, to change the course). Whereas this is regularly done in the boost phase today, aerodynamic course control during reentry into the atmosphere is still in the development stage and has only been introduced for one missile type (the U.S. Pershing 2). For ranges more than 100 km, the velocity of ballistic missiles is markedly above that of – even supersonic – aerodynamic ones. Ballistic missiles usually approach their targets at steep angles (from 20° to 70° elevation), and appear above the horizon of a target earlier than aerodynamic ones. Because of their higher velocity and smaller size, however, this does not necessarily mean that they are detected earlier.

As to the range of ballistic missiles, there has traditionally been some vagueness of terms. For land-based missiles, the term *strategic ballistic missile* has been defined in the SALT I Interim Agreement to mean a missile with a range above 5,500 km. For submarine-launched ballistic missiles, no lower range limit exists (the term strategic has been linked in the SALT II Treaty to the submarine type and the first flight test year). The term *intermediate-range ballistic missile* has traditionally been used to designate land-based missiles of range less than 5,500 km, and above about 1,000 km. The INF Treaty also used this language. For the range class between 500 km and 1,000 km, sometimes the name *operational-tactical ballistic missile* has been used. The INF Treaty denotes this class as *shorter-range missiles*. Ballistic missiles below 500 km range have been designated as *tactical*, or *short-range* ones.

For the purpose of the present study, the term *tactical ballistic missile* is used in a general, technically oriented sense; it means any ballistic missile with a maximum range between 60 km and 5,500 km. Sometimes, the range class below 500 km will be designated separately as *short-range ballistic missiles*. This classification is justified because the technical requirements of defense are determined by the range, and thus the velocity, of the missiles; sea-launched ballistic missiles, and possible future air-launched ones, of less than 5,500 km range, would fall into the same class. This definition intentionally excludes artillery rockets of, say, 15 or 30 km range for several reasons: they are similar to artillery shells, defense against them is not foreseen at present, and they are integrated into all other means of land warfare.

The term *anti-tactical ballistic missile system* (or *defense*) *(ATBM)* is used for any kind of system designed to counter tactical ballistic missiles in their flight trajectory. Such systems are the object of the present study. It does not treat other military missions which sometimes are included in a more general notion of *anti-tactical missile (ATM)* activity: the study does not deal with defense systems against aerodynamic missiles (they are included only insofar as separation from anti-tactical ballistic missile defense is concerned). It does neither analyze passive measures designed to reduce the effectiveness of tactical ballistic missiles (like hardening, dispersal, camouflage) nor offensive attacks against the launchers of tactical ballistic missiles prior to the missiles being launched (such strategies are mentioned shortly in the sections where motives and strategic stability are discussed).

The report gives the most weight to those defense technologies that could be deployed within the next 20 years, namely interceptor missiles based on the ground or possibly in space, with sensors located on the ground, in the air, and in space. More futuristic weapons concepts such as beam weapons are mentioned; a detailed analysis is not done here because system architectures are not well defined at present, and because several studies on general properties of such systems have been done in the context of the debate on the U.S. SDI project. Upgrading of existing air defense systems is covered only to a limited extent, because such modifications will provide no significant capability and because scientific-technical analyses are already available.

Whereas some political events and motives are mentioned in the chapter on the origins of the debate on anti-tactical ballistic missile systems, the study is devoted to the properties of such systems, and the consequences which their deployment would have, which derive from scientific and technical analysis. No political or military-strategic assessment is undertaken. Broader issues enter only in the form of the general realization that lasting security of potential opponents cannot be founded on ever-increased levels of military effectiveness.

Notes and References to Chapter 1:

1 Some recent literature on anti-tactical ballistic missile defense is: H.-G. Brauch, Anti-Tactical Missile Defense – Will the European Version of SDI Undermine the ABM Treaty?, AFES-Paper No. 1. Stuttgart: Arbeitsgruppe Friedensforschung und Europäische Sicherheit an der Universität Stuttgart, July 1985; T. Enders, Raketenabwehr als Teil einer erweiterten NATO-Luftverteidigung, Interne Studien Nr. 2/1986, Sankt Augustin: Sozialwissenschaftliches Forschungsinstitut der Konrad-Adenauer-Stiftung, January 1986; W. A. Davis, Jr., Regional Security and Anti-Tactical Ballistic Missiles: Political and Technical Issues, Washington etc.: Pergamon Brassey's, 1986; H.-G. Brauch, Militärische Komponenten einer Europäischen Verteidigungsinitiative (EVI), AFES-Paper No. 3, Stuttgart: Arbeitsgruppe Friedensforschung und Europäische Sicherheit an der Universität Stuttgart, June 1986; M. ter Borg, W. Smit (Eds.), Tactical Ballistic Missile Defence in Europe: Feasible, Affordable, Desirable?, Amsterdam: Free University Press, 1987; H. M. Feigl, Tactical missile defence, in: W. Stützle, B. Jasani, R. Cowen (Eds.), The ABM Treaty: To Defend or Not to Defend?, Oxford, New York: Oxford University Press, 1987; I. H. Daalder, The Artificial Consensus on NATO ATBMs, Working Paper no. 87-1, Cambridge MA: Harvard University, John F. Kennedy School of Government, June 1987; J. Altmann, B. Morel, T. Postol, T. Risse-Kappen, Anti-Tactical Ballistic Missile Defenses and West European Security, HSFK-Report 4/1987, Frankfurt/M.: Peace Research Institute Frankfurt, October 1987; H. van Gool, D. van Houwelingen, E. Schoten, Assessing ATBM, Boerderijcahier 8703, Enschede: University of Twente, Center for the Study of Science, Technology and Society 'De Boerderij', September 1987; G. Baechler, A. Statz, EDI – European Defense Initiative – Implications of Missile Defenses in Europe for West German Security Policy, Hamburger Beiträge zur Friedensforschung und Sicherheitspolitik, no. 12, Hamburg/Berlin: Institut für Friedensforschung und Sicherheitspolitik an der Universität Hamburg, December 1986; D. Rubenson, J. Bonomo, NATO's Anti-Tactical Ballistic Missile Requirements and Their Relationship to the Strategic Defense Initiative, Report RAND-3533-AF, Santa Monica CA: RAND Corporation, December 1987; D. L. Hafner, J. Roper (Eds.), ATBMs and Western Security – Missile Defenses for Europe, Cambridge MA: Ballinger, 1988.

2. Anti-Tactical Ballistic Missile Defenses: History and Trends

Section 2.1 takes a short look at the origins of the present debate on anti-tactical ballistic missile systems, which date back to the early fifties. 2.2 deals with two concepts which have been brought forward in the political discussions in NATO countries: Defense against missiles of all ranges, including nuclear ones (sometimes called "European Defense Initiative"), versus modest upgrading of air defense systems directed against conventional, and short-range, missiles. Ongoing research and development activities are described in 2.3.

2.1 Origins of the Debate on Anti-Tactical Ballistic Missile Defenses

2.1.1 Early history of Ballistic Missile Defense

The history of defense development against tactical ballistic missiles is at least as old as that of defense against strategic ones. The German V-2 missile used in the Second World War encouraged thoughts about defense systems against ballistic missiles. In the USA, projects began as early as 1946, i.e. five to ten years before the first intermediate-range and intercontinental ballistic missiles were operational.[1] During the fifties, development centered on a variant of the Nike-Hercules nuclear anti-aircraft missile for exoatmospheric interception (the Nike-Zeus). In the sixties, new phased-array radars and computers were integrated with very fast interceptors to a completely new project (Nike-X, later called Sentinel, with the Sprint missile) for endoatmospheric interception. While public controversy arose over deployment of nuclear interceptors in the vicinity of cities, and talks with the Soviet Union about limits on anti-ballistic missile (ABM) defenses proceeded, the main defense goal was changed from city protection to protection of intercontinental ballistic missile (ICBM) silos; the project Safeguard added the Spartan missile for exoatmospheric interception. One such system was deployed in North Dakota and became operational in 1975, but it was closed down again in 1976 for reasons of high cost and limited efficiency.

In the Soviet Union, ballistic missile defense programs started equally as early, and also came from air defense roots.[2] Some in the USA feared that the long-range anti-aircraft missile SA-5 (comparable to the U.S. Nike-Hercules) could be upgraded to an ABM capability. In the late sixties, the Moscow ABM system using phased-array radars and Galosh missiles for exoatmospheric interception was built.

The 1972 ABM Treaty with its 1974 Protocol allowed both sides to deploy ABM systems with no more than 100 interceptors in only one region. This treaty contributed to a decline of the interest in ballistic missile defense; research, development, and testing continued at a reduced pace. As stated, the USA does not have a deployed ABM system today; the USSR has continued its Moscow system and and is currently modernizing it, e.g. by adding faster interceptors (called Gazelle in the West) for endoatmospheric intercepts.

Specific projects for defense against tactical ballistic missiles started in the USA in 1951, but were overshadowed by the more important strategic defense programs.[3] In 1960 the first ballistic missile to be intercepted successfully was an Honest John (range 38 km), hit by a Hawk air defense missile launched simultaneously. This was more than two years before the first successful Nike-Zeus intercept of an intercontinental ballistic missile. In the sixties, new phased-array radar technology led to several new concepts, with differing requirements concerning the inclusion of air defense capabilities. These were AADS-70, Field Army Ballistic Missile Defense System (FABMDS) and SAM-D (later called Patriot). For the latter one, the requirement for anti-tactical ballistic missile defense was dropped at some stage in the development process mainly for cost reasons, leaving only the air defense role.

In the ABM debate of the late sixties in the USA, the other NATO countries discussed deployment of defense systems in Western Europe against Soviet intermediate-range missiles. Deployment of Safeguard systems in Europe was rejected for several reasons: their high cost and limited capability, the vulnerability of the radars, the availability of a broad spectrum of nuclear weapons carriers to the other side, and the problems created by nuclear interceptors.[4]

2.1.2 Technical Developments in Air Defense Systems

Technical progress in electronics, radar, and computer technology has allowed significant changes in air defense systems. Today, mobile phased-array radars can fulfill the detection, tracking, and guidance function with one system; modern computers and more reliable communication between interceptor and command station allow lower miss distances, and faster reactions. Thus the technical development arrives at a point where a non-nuclear defense capability against some classes of ballistic missiles (namely those of the shortest ranges, and equipped with conventional warheads) seems within reach.

In the USA, first tests of a modified modern air defense missile (the Patriot) against a Lance short-range ballistic missile (120 km range) and against another Patriot missile (ballistic range several hundred kilometers) have been performed.[5] Reports in the West indicate that the Soviet air defense system SA-10 has a capability against tactical ballistic missiles, and that the more modern SA-12 (which is roughly comparable to the U.S. Patriot) has been tested against the SS-12, a tactical ballistic missile of 900 km range, and against a target vehicle derived from an SS-4, which is an intermediate-range missile of 2,000 km range.[6]

2.1.3 Increasing Role of Conventional Ballistic Missiles Foreseen for Deep Strikes

With the upsurge of concepts for NATO attacks at WTO targets located in the rear (AirLand Battle, Follow-on-Forces Attack etc.) which could be observed in the early 1980s, several ideas for use of conventionally equipped tactical ballistic missiles emerged.[7] It was stated that with a circular error probable of 20 m and a payload of one metric ton, a ballistic missile could carry eight U.S. Air Force bunker target munitions of 100 kg each, resulting in a probability of destruction of above 0.8 for "almost all underground structures".[8] Three types of ballistic missiles have been discussed for transport of airfield-attack submunitions:

- The Conventional Attack Missile (CAM-40) with 550 kg payload would be similar to the Pershing 2 intermediate-range nuclear ballistic missile, and would likewise be terminally guided using radar area correlation, achieving a circular error probable of 30 to 50 m. Each missile would carry 68 or 112 kinetic energy runway penetrator munitions (KERP) of 8 kg each.[9] According to the producing firm, Martin-Marietta, 150 such missiles "could shut down 100% of the Warsaw Pact's main operating bases for several hours".[10] Studies by the U.S. Department of Defense are reported to have come to the conclusion that 53 Warsaw Pact airfields could be destroyed in 10 minutes by 50 ballistic weapons launched by two persons.[11]

- The Ballistic Offensive Suppression System (BOSS/Axe) of Lockheed Corporation would be based on the Tricent C-4 submarine-launched ballistic missile,[12] and could carry a payload of 6300 kg of airfield defeat munitions to a range of 650 km.
- The Total Air Base Attack System (TABAS) would be even larger; its 25-metric-ton payload would be carried by a giant missile similar to the Saturn rocket.[13] (The complete Saturn V was about 100 m long and had a launch mass of 2,750 t.[14])

Some commanders would like to be able to, "when war starts, immediately put 40 airfields out of action".[15] Others, however, emphasize the difficulties of closing an airfield with conventional ballistic missiles.[16] Many of the advertised damage probabilities seem greatly exaggerated, if one takes into account the insufficient targeting accuracy and the availability of reserve runway area (see 7.2). That such attack concepts would nevertheless raise severe problems because the missiles could not reliably be recognised as non-nuclear, is acknowledged in some of the articles cited.[17] Whereas some defense specialists explicitly recommend introduction of new precise ballistic missiles with conventional munitions into NATO's arsenals,[18] the prospect of the necessity of early use of fast weapons, and the conventional-nuclear ambiguity has created significant unrest about crisis stability and escalation risk within parts of the North Atlantic Assembly.[19] The INF Treaty of December 1987 with its elimination of all U.S. and Soviet ground-launched missiles with ranges between 500 and 5,500 km will prevent most of those concepts from developing. (And it will of course, at the same time, reduce existing threats by ballistic missiles of those ranges, as long as smaller NATO and WTO countries will not circumvent its provisions.)

For attacks at less than 500 km depth, a follow-up to the Lance missile is being developed. The U.S. Army Tactical Missile System (A)TACMS is to carry conventional submunitions, possibly equipped with homing guidance. Targets would be airfields and troop concentrations, and also tactical ballistic missile launchers of the WTO.[20] The ATACMS would be launched from a multiple-launch rocket system (MLRS) launcher; one version (T-16) is based on the Patriot air defense missile, another (T-22) rests upon a modified Lance short-range ballistic missile.[21] The range is mostly given as below 200 km. There has always been some discussion about a nuclear warhead, but the U.S. Congress has limited ATACMS to a non-nuclear role.[22] Only recently, after the conclusion of the INF Treaty, U.S. Government plans for the Lance follow-up seem to have been changed to a range of 450 km and a nuclear warhead.[23]

Concerning tactical ballistic missiles of the Warsaw Treaty Organization, there have traditionally been more missiles than NATO had in Western Europe. Whereas most types have been equipped with nuclear warheads, it is reported that the newer generation being introduced since about 1980, the SS-21 (100 km range), the SS-23 (500 km range), and the SS-12 mod. (900 km range), could also be equipped with conventional (and chemical) warheads.[24] Although the present accuracy of about 300 meter circular error probable [25] excludes any efficient use against military targets, some worst-case analyses foresee drastic improvements in targeting precision for the next years.[26] A U.S. Department of Defense official once mentioned an accuracy of 30 m for upgraded models of the SS-21, SS-12 mod., and SS-23.[27] For the near future, however, such claims are implausible. The accuracy limit which can be achieved with modernized high-quality inertial guidance is about 50 m, but it is unclear if the expense and maintenance difficulties for such a system could be warranted.[28] Furthermore, the launch sites would have to be surveyed to less than 50 m accuracy, and mobile targets could not be hit. Only with target recognition and terminal guidance systems like that used in the U.S. Pershing 2 missile, can values of the circular error probable of 30 to 40 m be achieved. There is no doubt that such technology could also be used by future Soviet ballistic missiles, but this would require a major redesign; in addition, the bulky radar and power supply system of about 300 kg would represent a significant amount of the payload of about 1,000 kg;[29] unlike a nuclear warhead, this would directly affect the effectiveness of the conventional munitions carried.[30]

The difficulties of conventional ballistic missile attacks mentioned above, of course also apply to the missiles of the WTO. Results of a study on the threat to NATO by WTO conventional tactical ballistic missiles indicate that this threat is of no great relevance because of limited payload, target location uncertainty, and limited missile numbers; aerodynamic missiles for many conceived tasks would be inherently more appropriate than ballistic ones.[31] (These results are summarized in 7.2.)

Perceptions about the decisive effect which a surprise attack by conventional ballistic missiles could have,[32] are one of the main driving factors behind the efforts to develop anti-tactical ballistic missile defenses, even if they are not based on sound technical and strategic analysis.

In order to cope with the ballistic missile threat, attacks at their launchers by Western conventional ballistic missiles have in many instances been recommended (in spite of the problems already mentioned).[33]

2.1.4 The Strategic Defense Initiative of the USA

The biggest push increasing the interest in anti-tactical ballistic missile systems has come from the U.S. SDI program.[34] With SDI, defense against ballistic missiles has changed from a marginal role since the conclusion of the ABM Treaty to a major national goal. Connections between defense against strategic and defense against tactical ballistic missiles exist on the technical side because of range overlap, and thus similar trajectories, for some missile types. Especially with terminal defenses, use of the same interceptor systems is foreseen for both roles, and first tests of SDI weapons have been conducted against short-range ballistic missiles.[35] It is in the SDI context that the possibility of using nuclear warheads on anti-tactical ballistic missile interceptors has sometimes been mentioned.[36] Air- and space-based components for detection of missiles or warheads can likewise be used for strategic as well as for tactical ballistic missiles, and are planned for use in both regions, continental USA and Western Europe.[37] On the judicial side, development and deployment of anti-tactical ballistic missile defenses in Western Europe was recommended in 1983 by the Hoffman panel as a means of gaining experience with interceptor systems without the need for early withdrawal from the ABM Treaty.[38] Another motive, reducing "allied anxieties that our increased emphasis on defenses might indicate a weakening in our commitment to the defense in Europe", was also mentioned by the panel.[39] The declared motives which led West European governments to cooperate in SDI with inclusion of theater defenses were e.g. participation in technologies, and receiving research money for West European armament firms.[40] Whereas some incremental upgrading of air defense systems would be underway anyway (and had been planned for several years before the SDI project was launched), it is highly unlikely that defense against Soviet tactical ballistic missiles would have gained such a prominent role, had there not been the U.S. SDI project.[41]

2.2 "European Defense Initiative" or "Extended Air Defense"? – Two Different Concepts for Anti-Tactical Ballistic Missile Systems

Shortly after having understood that the U.S. SDI project was not a short-lived fancy, West European conservatives started demanding similar protection for West European countries as SDI would supposedly grant to the USA.[42] Others coined the term "European Defense Initiative" (EDI)for a research and development program paralleling the U.S. SDI project, but without claiming that population protection from Soviet tactical ballistic missiles would be achievable.[43] SDI proponents talked of popping up mirrors for laser weapons in Europe and conveyed the impression that EDI would be much easier than SDI.[44] Later, however, the "European Defense Initiative" notion was only used by groups at the margin of the security debate. The High Frontier Europa Organization (connected with the corresponding U.S. organization), explicitly demands a multi-layered defense against Soviet missiles aimed at Western Europe, including West European beam weapons on high mountains and deployed in space, capable of attacking Soviet missiles in their launch phase.[45] Its chairman, former West German Defense Minister K.-U. von Hassel, states that "SDI and EDI will allow a change from the current strategy of Mutual Assured Destruction (MAD – continuous blackmail and revengeful destruction) to a strategy of Dissuasion, strengthening Deterrence, based on the denial of assured destruction."[46] Only the Fusion Energy Foundation has been more explicit in promising protection of the West European population from Soviet nuclear missiles.[47]

The West German Defense Ministry, on the other hand, has been careful to avoid the term "European Defense Initiative". Besides the different character of the nuclear threat to Western Europe, as opposed to the USA, this probably has to do with several political motives: the chances for population protection are even smaller than for the U.S.; in the West German public, there is widespread scepticism and opposition to the introduction of space weapons (this holds not only for the peace movement, but also for the political establishment, including parts of the governing liberal and conservative parties, FDP and CDU); undercutting nuclear deterrence by moral arguments is to be avoided; and development of anti-tactical ballistic missile defenses is to be separated from the highly criticized SDI project and its possible failure within a couple of years.[48] The Defense Ministry has introduced the category of "Extended Air Defense" instead, which sounds like a logical continuation of legitimate and traditional efforts, and does not suggest a revolution in nuclear strategy. The Ministry promotes adding defense against conventional aerodynamic, and short-range ballistic missiles to the capabilities of upgraded ground-based air defense systems.[49] These systems have to be non-nuclear.[50] Overlap with SDI activities is acknowledged to exist in the field of terminal-phase defense techniques, but "otherwise the project of a missile defense in Europe is independent of SDI. It would have to be put into action as well, if SDI did not exist or would not be realized."[51]

When judging this concept and the extent to which it is separate from SDI and the notions connected with it, one should, however, take into account several inconsistencies: First, future options of space-based sensors are not excluded. Second, for M. Wörner it was just the inclusion of defense against Soviet *nuclear* short- and intermediate-range ballistic missiles into the integrated SDI concept of the USA, which "allowed the Federal Government to oppose various conceptions of ... a space-based European ballistic missile defense system (EDI = European Defense Initiative)".[52] Third, in an answer given to a question by a member of the West German Parliament, the Defense Ministry explicitly included every kind of existing nuclear, tactical and intermediate-range, ballistic missile of the USSR into the list of missiles against which "Extended Air Defense" was to be directed, even the SS-20 which with its trajectory and multiple independently targetable reentry vehicles rather resembles an intercontinental ballistic missile.[53] Fourth, the U.S. SDI organization viewed air defense upgrades as a first step in the process of gradual buildup of global defense systems. Several West European firms have been granted contracts from the U.S. SDI Organization to define and evaluate several alternate concepts for defenses which would negate the theater missile threat, with primary emphasis on short-range ballistic missiles. The request for proposals called for evolutionary architectures which "shall be defined to include identification of near, mid- and far-term architectures. The near-term architectures shall include contributions from incremental improvements to existing [and] planned systems. An assessment of theater defense capability to exist and operate by itself, and potential for integration into a global strategic defense architecture, will be accomplished."[54] (See also 2.3.3.)

2.3 Ongoing Activities for Anti-Tactical Ballistic Missile Defense in NATO Countries

2.3.1 Upgrading of Air Defense Systems

2.3.1.1 Patriot

The U.S. air defense system Patriot, which has been deployed since 1986, and will also be utilized by Italy, Japan, the Netherlands, West Germany, and possibly Belgium,[55] is to be modified in two or three steps.[56] The first (Patriot Anti-tactical missile Capability, PAC 1) mainly consists of a software change, enlarging the radar solid angle for search and interceptor guidance to elevations where ballistic missiles would enter; this has been deployed since 1988. PAC-2 will comprise a change of the warhead (larger fragments, modified fuzing) to increase the efficiency against ballistic missiles. These modifications are aimed at a capability against ballistic missiles from 100 to 900 km range. In order to defend against the intermediate-range SS-20 (5,000 km range), PAC-3 had been planned (probably including a new booster stage); but this competes with the FLAGE missile (see 2.3.4). A Patriot modified similarly to PAC-1 intercepted a Lance short-range ballistic missile in a test on September 11, 1986.[57] A Patriot modified according to PAC-2 intercepted another Patriot flying in a ballistic trajectory on November 4, 1987.[58]

2.3.1.2 Medium Surface-to-Air Missile

The Medium Surface-to-Air Missile MSAM is planned as a follow-up to the Hawk air defense missile, and is to be deployed from the late 1990s on. Three alternative types are discussed:[59]

- The U.S. Evolved Hawk (Raytheon Corporation) with a rotating phased-array radar will be available early at a relatively low cost. Use against tactical ballistic missiles would, however, require cooperation with a Patriot radar.
- The West German Taktisches Luftverteidigungssystem TLVS (being developed by the firms MBB, Siemens, and AEG) will have thrust vector control and lateral thrusters. With a rotating phased-array radar for search and initial guidance and an on-board radar for terminal guidance, it is to provide a capability against aircraft, aerodynamic missiles and tactical ballistic missiles. At a relatively high cost, it will be available only around the year 2000.
- The SA-90 developed by the French firms Aerospatiale and Thomson-CSF is to be fielded in the mid-1990s in a sea-based (SAAM) and a land-based (SAMP) version. The Aster missile also possesses lateral thrusters for high maneuverability above the low atmosphere. Designed against aircraft, cruise and stand-off missiles, as well as short-range ballistic missiles, a capability against tactical ballistic missiles above 500 km range would require major modifications, including a new boost stage.

2.3.2 NATO Studies

In 1982 NATO passed the Counterair '90 study, a long-term program for fighting the WTO air potential. It comprises air defense, offensive counter air (i.e. strikes against WTO aircraft on the ground, against air bases and air defense systems); attacks against launchers of short-range ballistic missiles; and defense against tactical ballistic missiles.[60]

After President Reagan's SDI speech of 1983, the NATO Military Committee commissioned the Advisory Group for Aerospace Research and Development AGARD to do a study on technical possibilities of active defense against Soviet tactical ballistic missiles up to the year 2000. The scope was limited to ranges below 1,000 km, and to non-nuclear defense systems. The Aerospace Application Study AAS-20 was finished in 1986; it is classified, but some results have been reported by T. Enders:[61] For the time frame analyzed, mainly ground-based interceptor missiles can be used, no contribution from electromagnetic launchers or beam weapons can be expected. Upgraded Patriot systems could provide defense capabilities against the SS-21, SS-23, and SS-12 mod. missiles (with ranges from 100 to 900 km). For increased interception distances, airborne infrared sensors like those worked on in the U.S. SDI program would be needed; in addition, sensors based in space or popped up on rockets would be required.

After that, AGARD was commissioned to do a follow-up study (AAS-25), in which a detailed assessment of the threat by non-nuclear tactical ballistic missiles is to be made.[62]

Several other organizations within NATO are involved in producing studies related to the question of anti-tactical ballistic missile defense. These include the SHAPE Technical Center, the staff of the Supreme Allied Commander for Europe, and the Air Defence Committee.[63] At the NATO Headquarters, a ballistic missile defense Project Board has been formed.[64]

2.3.3 SDI Architecture Studies

In 1986, the SDI Organization founded a new sub-unit "Theatre Architectures and Programs".[65] The SDI Organization has given contracts for the study of European theater missile defense architectures to several consortia. In Phase 1, seven teams were selected in December 1986 to receive $ 2 million each.[66] In Phase 2, five consortia have received up to $ 4.5

million each (with an optional increase to $ 7 million) for a period from September 1987 to July 1988.[67] Here, detailed subsystem specifications, development and deployment plans, as well as cost estimates are to be provided. Besides U.S. firms, corporations from France, Great Britain, Italy, and West Germany are participating. In a separate architecture study, anti-tactical ballistic missile defense technologies applicable to the Middle East theater are analyzed by U.S. and Israeli corporations.[68]

The joint services of the USA have launched a task force to coordinate and evaluate an overall antitactical missile program. As part of this, the Strategic Defense Command of the U.S. Army (for the SDI Organization) administers the Invite, Show and Test (IST, ISAT) program; here, U.S. and allied corporations can bid for systems and subsystems (in the fields of kill mechanisms, sensors, battle management, and components) for a near-term theater missile defense system.[69] In the Combined Allied Defense Experiment (CADE), system, test, and hardware support for all kinetic energy weapons regional defense programs are provided.[70] The SDI Organization has set aside $ 50 million for cooperative experiments, demonstration projects, and development with allied nations.[71]

2.3.4 Development of Anti-Tactical Ballistic Missile Defense Systems Within SDI

The Report to the Congress 1987 of the SDI Organization states that space-based weapons could engage tactical and intermediate-range ballistic missiles like the SS-12 mod. (900 km range) and the SS-20 (5,000 km range) in their boost phases. For shorter ranges, terminal defenses are mentioned like endo- and exoatmospheric interceptors.[72] (The 1988 Report provides more technical detail; concerning the INF Treaty, it argues that short-range ballistic missiles will remain in the Soviet inventory, that intercontinental and submarine-launched ballistic missiles could be used against the U.S. allies, and that intermediate-range ballistic missiles are not proscribed for other nations. Thus, "the requirement for theater missile defense (TMD) remains intact."[73]) This means implicitly that any kind of new weapon developed in SDI for defense against strategic ballistic missiles is seen as a possible contributor to regional ballistic missile defenses. Explicitly listed for that purpose are some ground-based kinetic energy weapons technologies and systems like electromagnetic interceptors or the FLAGE follow-on and its successor, the Extended Range Interceptor ERINT for low endoatmospheric interception.[74] According to a Regional Defense Concept depicted in the Report, interceptors like the HEDI for high-endoatmospheric, and ERIS for exoatmospheric interception are also planned, as well as air- and space-borne infrared sensors (the Airborne Optical System, the Space Surveillance and Tracking System).[75] The Strategic Defense Command of the U.S. Army has been designated as the SDI executive agent for managing the tactical missile defense portion of the SDI, and the cooperation with NATO countries and Israel.[76]

2.3.5 West European Activities

As part of the Patriot-Roland agreement, West Germany funds anti-tactical missile studies with an amount of $ 50 million. Of this amount $ 26 million is for a classified project, $ 5 million will be used for building alternate runways (i.e., passive countermeasures against airfield attack), and $ 17 million will be spent for anti-tactical missile improvements.[77] The last figure contains $ 8.5 million for an improved Patriot guidance system and for a new extended range motor, and $ 8.7 million for threat analysis, combat modeling, and command and control studies. The remaining $ 2 million will be used to develop an active seeker for the Patriot.

France and West Germany are undertaking a separate study on anti-tactical ballistic missile defenses for their own requirements.[78]

West European armament firms have increased their efforts in the ballistic missile defense area. To give a few examples from West German firms: MBB has founded a new department "Defense Initiatives".[79] Plans for the new tactical air defense system TLVS include (limited) capability against ballistic missiles (see 2.3.1.2).[80] Rheinmetall is working on electromagnetic guns.[81] For a couple of years, MBB and Diehl have been developing ground-based mobile laser weapons; their possible future use for anti-tactical ballistic missile defense has been mentioned.[82]

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8 Wikner (note 7).

9 With two stages, such a missile could reach all WTO main operating bases from anywhere in Western Europe, a one-stage version could cover 70% of the WTO main operating bases. See: Wikner (note 7); R. R. Ropelewski, Firm Studies Counter-Airfield Weapon, Aviation Week & Space Technology, pp. 73-74, August 29, 1983.

10 Ropelewski (note 9).

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15 General C. Gabriel, Chief of Staff of the U.S. Air Force, Interview of January 1982, see: Wikner (note 7).

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3. Tactical Ballistic Missiles

In this chapter, the main characteristics of tactical ballistic missiles will be dealt with, starting with their trajectories (3.1). Guidance and targeting accuracy will be covered in 3.2, and the damage produced at targets is described in 3.3. Section 3.4 lists properties of existing and planned tactical ballistic missiles.

3.1 Trajectories of Ballistic Missiles

3.1.1 Exact Calculation – Forces and Moments

In general, a rocket moves under the influence of four main forces which will be described briefly in the following:

The *gravity* force is directed along the local vertical (which normally differs slightly from the direction to the center of the earth), its magnitude is

$$F_G = m(t)\, g(h), \tag{3-1}$$

where $m(t)$ is the actual rocket mass at time t and $g(h)$ is the gravity acceleration at the actual rocket altitude h.

As long as the rocket or its reentry vehicle is within the atmosphere, two aerodynamic forces apply: The *drag* force has its direction opposite to the vector of the relative velocity between rocket and air, with the magnitude

$$F_D = c_D(M, \alpha)\, \rho(h)\, v^2(t)\, A / 2. \tag{3-2}$$

Here the drag coefficient c_D depends on the Mach number $M = v(t) / v_S(T, m_{mol})$, the ratio of the actual velocity v and the local velocity of sound, which itself depends on the local temperature and mean molecular mass, and on the angle of attack α between the rocket axis and the velocity vector; $\rho(h)$ is the altitude-dependent air density; and A is the cross sectional area of the rocket or reentry vehicle.

The direction of the *lift* force is normal to the drag force in the plane of the velocity vector and the rocket axis. Its magnitude is

$$F_L = c_L(M, \alpha)\, \rho(h)\, v^2(t)\, A / 2, \tag{3-3}$$

where the lift coefficient c_L depends on the same quantities as the drag coefficient.

During the boost phase, the *thrust* force is the biggest force. It is usually directed in the rocket axis, its magnitude being

$$F_T = \dot{m}\, v_e + A_e\, (P_e - P_0(h)); \tag{3-4}$$

here the rate of mass exhaust $\dot{m}$ and the exhaust velocity v_e are normally constant over the burn time of any stage; A_e and P_e are the nozzle exit area and the exhaust pressure at the nozzle exit, respectively, and the exterior air pressure P_0 depends on the altitude h.

These forces have to be added vectorially to yield the total force **F**, from which then, according to Newton's law, the acceleration vector **a** can be calculated:

$$\mathbf{a} = \mathbf{F} / m(t). \quad (3\text{-}5)$$

The movement of the center of gravity of the missile can then be computed numerically by twofold integration. Besides the irregularities already implicit in (3-1) to (3-4) (e.g. gravitation anomalies, seasonal and diurnal atmospheric variations), an exact calculation would have to allow for additional factors like the rotation and movement of the earth, winds, maybe even precipitation, variation of aerodynamic coefficients with ablation, etc.

Not all force vectors act at the center of gravity (which, incidentally, shifts with increasing fuel consumption); e.g., the aerodynamic forces are applied at the center of pressure. Thus, moments evolve and the rotation of the rocket about its three axes has also to be taken into account. This leads to the field of flight stability and guidance. The position of aerodynamic control surfaces or the direction of the thrust vector, are normally varied in order to keep the rocket in the correct attitude on its pre-planned trajectory during the boost phase.[1] Very complicated computer programs are required if all effects of rocket motion are to be simulated. Since the details of the guidance laws are not important for the considerations of the present report, trajectory computations are done using only the main forces and a standard atmospheric model; moment effects are not included (see Appendix).

3.1.2 Approximative Formulae

3.1.2.1 Keplerian Motion Through Space

One of the main characteristics of a ballistic missile is its maximum range. If one disregards the atmosphere, the rotation and non-sphericity of the earth, and the acceleration phase of the missile, the maximum range r_{max} can be derived from the Keplerian motion along the minimum energy ellipse:[2]

$$r_{max} = 2\, R_E \arcsin\left(\frac{(v_B/v_c)^2}{2-(v_B/v_c)^2}\right). \quad (3\text{-}6)$$

Here

$$v_c = (\mu / R_E)^{1/2} = 7.91 \text{ km/s} \quad (3\text{-}7)$$

is the circular velocity at altitude 0 ($\mu = \gamma M_E = 3.986 \cdot 10^{14}\ m^3 s^{-2}$ is the product of Newton's constant of gravity and the mass of the earth, $R_E = 6.370$ Mm is the earth radius), and v_B is the burnout velocity (here it is assumed that v_B is achieved immediately at altitude 0).

In order to enter a minimum energy trajectory, the velocity vector at burnout must be inclined with respect to the horizontal by a certain angle α_{Brmax}:

$$\alpha_{Brmax} = \arccos\left(\frac{1}{(2-(v_B/v_c)^2)^{1/2}}\right). \quad (3\text{-}8)$$

The maximum altitude h_{max} for any elliptical trajectory is derived using the greater half axis a and the eccentricity e:

$$a = R_E / (2-(v_B/v_c)^2), \quad (3\text{-}9)$$

$$e = [\,1-(v_B/v_c)^2\ (2-(v_B/v_c)^2)\cos^2\alpha\,]^{1/2}, \tag{3-10}$$

$$h_{max} = a\,(1 + e) - R_E. \tag{3-11}$$

Fig. 3-1 shows how the burnout velocity and angle, the maximum altitude, and the flight time vary with maximum range. In reality, (3-6) to (3-11) can be used for that part of the flight which goes through the vacuum of space; altitude, range and flight time have to be increased according to the boost and reentry phases.

3.1.2.2 Rocket Mass Considerations

Another basic property of a missile is the ratio between its launch mass and its payload. A rough estimate of this can be made using the rocket equation

$$v_{Bth} = v_e \ln\left(\frac{m_0}{m_B}\right) \tag{3-12}$$

(v_{Bth}: theoretical burnout velocity; m_0: launch mass; m_B: mass at burnout). The exhaust velocity v_e, which divided by the acceleration of gravity gives the so-called specific impulse, can amount to 2.6 km/s at sea level for today's most modern solid propellants (in the sixties 2 km/s were typical); in the vacuum of higher altitudes, values of 2.9 km/s can be achieved. (Cryogenic liquid fuels for civilian space rockets give up to 4 km/s at sea level.)[3] For multiple-stage rockets, the total theoretical burnout velocity is given by the sum of the contributions from each stage, which are given by (3-12) if the appropriate masses are used.

If one ignores the mass of the missile itself (i.e., the launch mass m_0 consists only of the payload mass m_p and the fuel mass, therefore no separate stages are necessary), a lower bound on the m_0/m_p ratio is

$$\frac{m_0}{m_p} = e^{v_{Bth}/v_e}. \tag{3-13}$$

With a typical exhaust velocity of $v_e = 3$ km/s, achieving a burnout velocity of 1 km/s requires a launch mass more than 1.4 times the payload; for 2 km/s, the ratio has to be greater than 2. Fig. 3-1 contains the theoretical minimum launch mass – payload mass ratio necessary for the different ranges for a rocket with $v_e = 3.0$ km/s. In reality, of course, the missile housing, the nozzle, pumps (in the case of liquid fuels), guidance systems etc., contribute to the mass at burnout, increasing the launch mass – payload mass ratio; more than one stage is used for missiles with a range of over 500 km in order to reduce this effect.

3.1.2.3 Boost Phase: Effects of Finite Acceleration and of the Atmosphere

A ballistic missile is accelerated during a finite boost phase; during this time, it is subjected to gravity and to drag forces. Both reduce the actual velocity at burnout v_B:

$$v_B = v_{Bth} - \Delta v_G - \Delta v_D, \tag{3-14}$$

where

$$\Delta v_G = \int_0^{t_B} g \sin \alpha \, dt, \qquad (3\text{-}15)$$

$$\Delta v_D = \int_0^{t_B} c_D \, \rho \, v^2 \frac{A}{2\,m} \, dt \qquad (3\text{-}16)$$

are integrated over the burn time t_B (ρ: air density). The velocity loss due to gravity Δv_G contains the (altitude-dependent) gravity acceleration g and the (trajectory-dependent) angle α between the momentary velocity vector and the local horizontal. For vertical launch, it can be approximated by the product of the gravity acceleration on the ground and the burn time. The velocity loss due to drag Δv_D depends on the momentary values of the drag coefficient c_D (which varies with Mach number $M = v / v_S$, v_S: local velocity of sound, which itself depends on local temperature and molecular mass), the velocity v, the (altitude-dependent) air density ρ, the missile cross section A, and the mass m (which decreases as burnt fuel is ejected). Both quantities thus depend in a complicated way on the missile launch parameters; minimizing the loss due to gravity leads to short burn times and high acceleration, whereas in order to decrease the loss due to drag, one tends to accelerate slowly to avoid high velocities, in altitudes where the air density is still considerable. By the same token, the trajectory will be kept vertical through the denser layers of the air. Due to gravity effects, the burnout velocity may typically decrease by 0.3 to 0.7 km/s; the loss due to drag may amount to 0.1 to 0.3 km/s.

In the case of both very short range (100 km and below) and air defense missiles, a significant part of the trajectory is within the atmosphere. Here a non-vertical launch is often used. In this case, lift forces at the missile body and its control surfaces can help to compensate for gravity.

3.1.2.4 Reentry

When a missile or its payload reenters the atmosphere with roughly its burnout velocity, a drag force will again be experienced. Since the atmospheric density increases nearly exponentially along the trajectory, at some altitude the deceleration will increase markedly. Consequently, the velocity will decrease sharply, whereby, in turn, deceleration decreases again. If one assumes an exponential density profile, a linear trajectory of sufficient inclination (i.e., constant angle $\alpha < -10^\circ$ with the horizontal), constant drag coefficient c_D, and zero lift, the velocity v at altitude h is [4]

$$v(h) = v_R \exp \left(H_S \, \rho(h) / (2 \, \beta \sin \alpha) \right), \qquad (3\text{-}17)$$

where v_R is the reentry velocity, $H_S = 6.7$ km is the density scale height, $\rho(h) = \rho_0 \exp(-h / H_S)$ is the air density at altitude h ($\rho_0 = 1.752$ kg/m^3 is the density at the ground, appropriate for the exponential model). The so-called ballistic coefficient

$$\beta = \frac{m}{c_D A} \qquad (3\text{-}18)$$

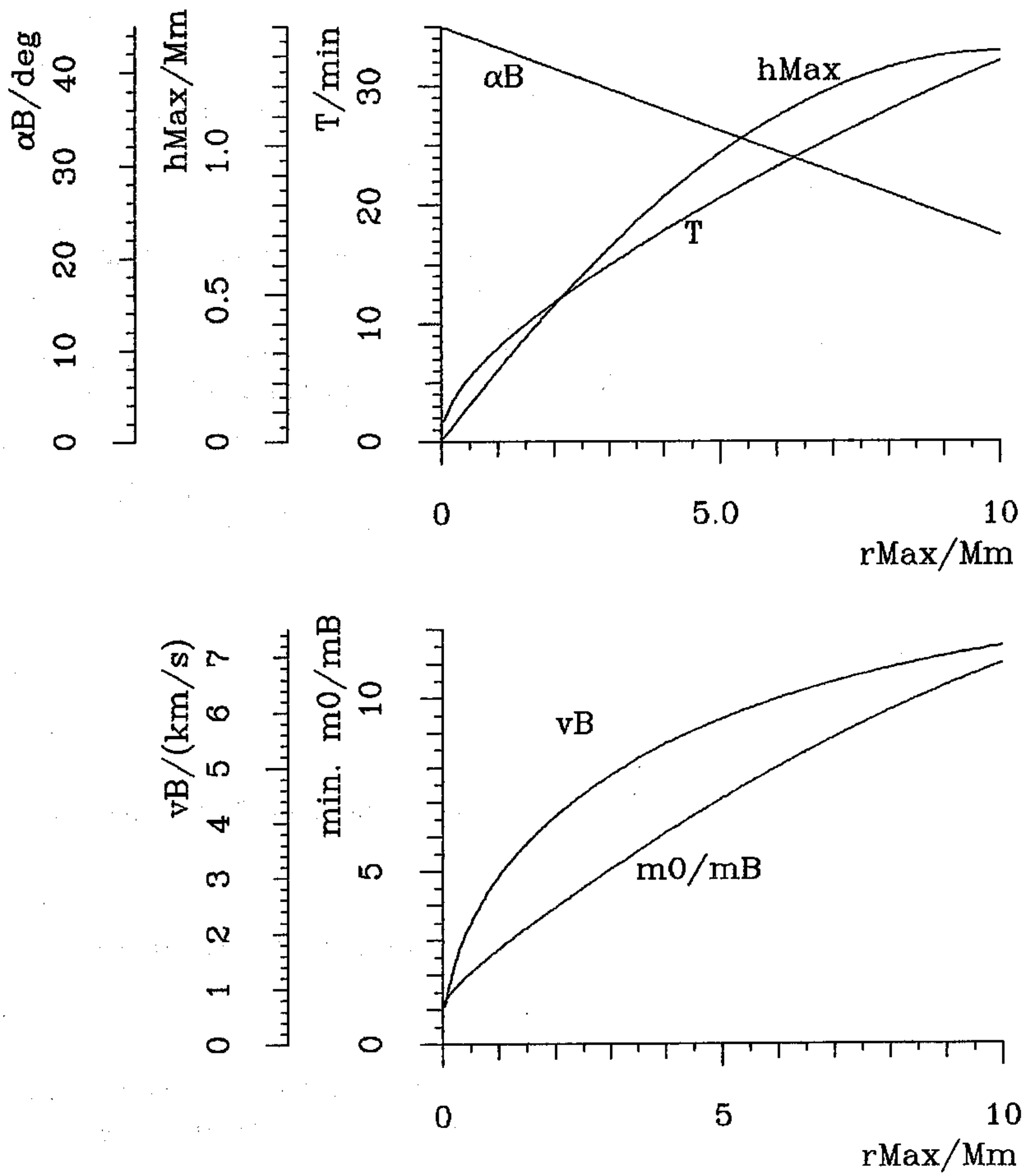

Fig. 3-1 Variation of parameters with range r_{max} in megameter (= 1,000 km) for a hypothetical minimum energy trajectory in vacuum, which starts at altitude 0. α_B: angle to horizontal in degree, h_{max}: maximum altitude in km, T: flight time in minutes (see Appendix), v_B: burnout velocity in km/s. In addition, the theoretical minimum launch/burnout mass ratio m_0/m_B for an ideal massless rocket (i.e., one consisting only of fuel and payload) with v_e = 3 km/s exhaust velocity is plotted.

combines the vehicle-dependent parameters entering the drag relation (3–2) (here, c_D is normally taken as constant). Typical values for reentry vehicles of strategic ballistic missiles of the early seventies were about 5,000 kg/m^2 for the USA, considerably less for the USSR; today, US strategic reentry vehicles have ballistic coefficients of 8,800 – 9,800 kg/m^2, and those of the USSR amount to 7,300 – 8,800 kg/m^2.[5] The maximum deceleration is

$$a_{max} = \frac{v_R^2 \sin\alpha}{2\,e\,H_S} \tag{3-19}$$

(e = 2.71828...), regardless of the ballistic coefficient β. It occurs at the altitude

$$h_{amax} = H_S \ln\left(\frac{\rho_0 H_S}{\beta \sin\alpha}\right), \tag{3-20}$$

which is not dependent on the reentry velocity. The velocity at maximum deceleration is

$$v_{amax} = v_R / \sqrt{e} = 0.607\, v_R. \tag{3-21}$$

Due to aerodynamic friction, the vehicle experiences heating. Under certain assumptions, the momentary rate of heat energy influx (i.e., the power) P can be approximated by

$$P = c_F\, \rho\, S\, v^3 / 4 \tag{3-22}$$

where c_F is the equivalent skin–friction coefficient (this takes a typical value of the order of 0.001)[6], and S is the wetted surface area. This takes a maximum value of

$$P_{max} = c_F\, S\, v_E^3\, \frac{\beta \sin\alpha}{6\,e\,H_S} \tag{3-23}$$

at the altitude

$$h_{Qmax} = H_S \ln\left(\frac{3}{2}\,\frac{\rho_0 H_S}{\beta \sin\alpha}\right), \tag{3-24}$$

which is about 1.10 times the altitude of maximum deceleration (3-20). The velocity at this point is

$$v_{Qmax} = v_R / e^{1/3} = 0.717\, v_R. \tag{3-25}$$

The total heat energy that has flowed into the vehicle during reentry is approximately

$$Q = m\,(v_R^2 - v_I^2)\, \frac{c_F\, S}{4\, c_D\, A}, \tag{3-26}$$

where v_I is the impact velocity; $c_F S / (2\, c_D A)$ describes the fraction of total kinetic energy lost that has flowed into the vehicle, a typical value is 0.05 (the other, larger portion has gone into the wake).[7]

Another important thermal parameter is the heat energy influx per area at the point of highest power, the stagnation point (i.e., the nose center). The time rate of change of this quantity, i.e., the quotient of the heat power at the stagnation point P_S and the area A, can be approximated by [8]

$$\frac{P_s}{A} = \frac{C}{r_n^{1/2}} \left(\frac{\rho}{\rho_0}\right)^{1/2} \left(\frac{v}{v_c}\right)^3, \tag{3-27}$$

where $C = 3\ \mathrm{MW/m^{-3/2}}$ is an empirical constant, $v_c = 7.91$ km/s is the circular velocity at sea level, and r_n is the nose radius.

In order to protect its interior, a reentry vehicle has a heat-absorbing and insulating casing, the material of which partially ablates. Typically, for longer ranges composites of carbon

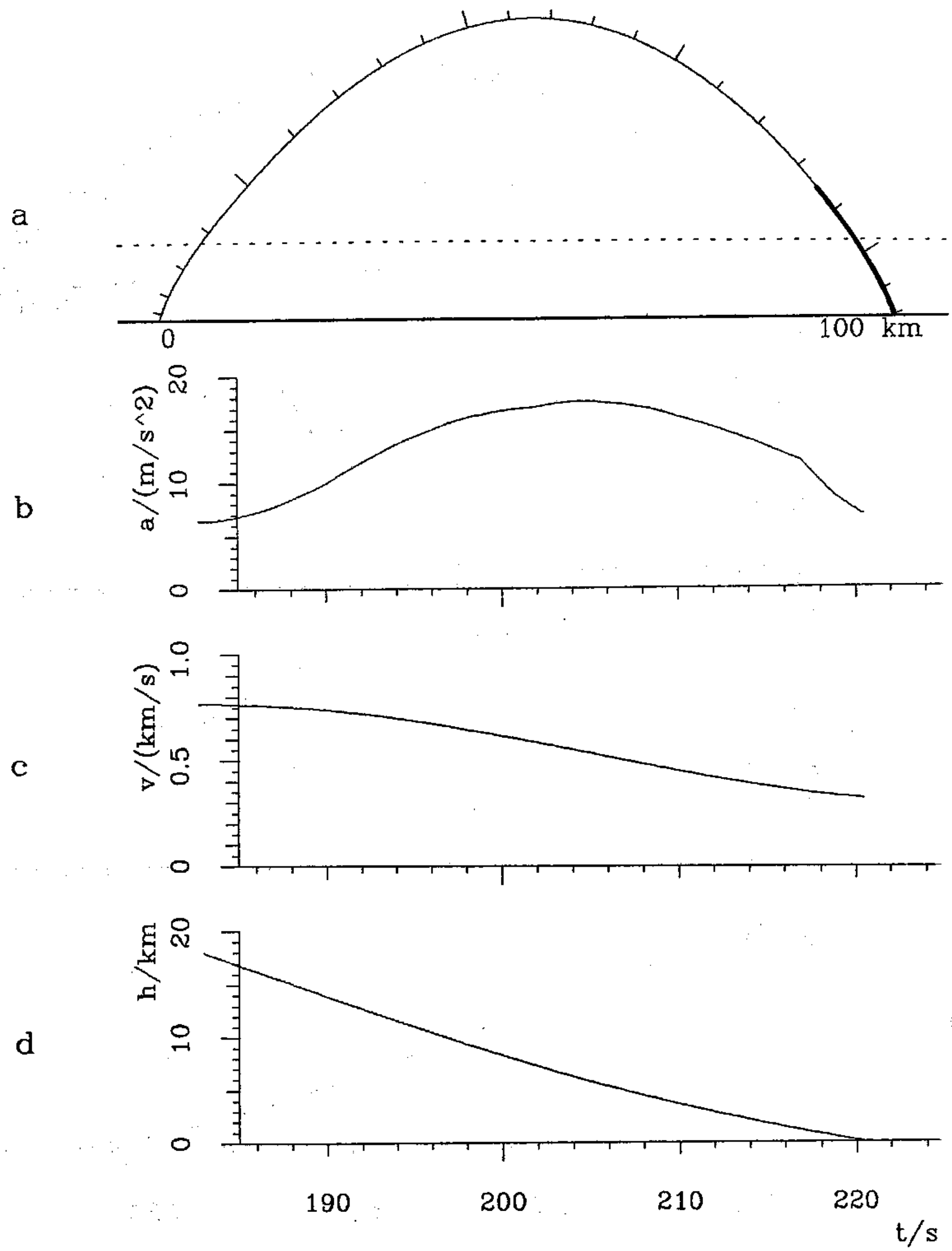

Fig. 3-2 Total trajectory and terminal flight phase of a short-range ballistic missile over 100 km range (ballistic coefficient of entire missile $\beta = 4{,}800\ kg/m^2$), computed with the program described in the Appendix.
a) Total trajectory. One tick corresponds to 10 seconds. The dotted line marks 10 km altitude. The terminal flight phase is indicated.
b) Deceleration a in m/s^2,
c) Velocity v in km/s,
d) Altitude h in km,
during the terminal flight phase, versus time t after launch in seconds.

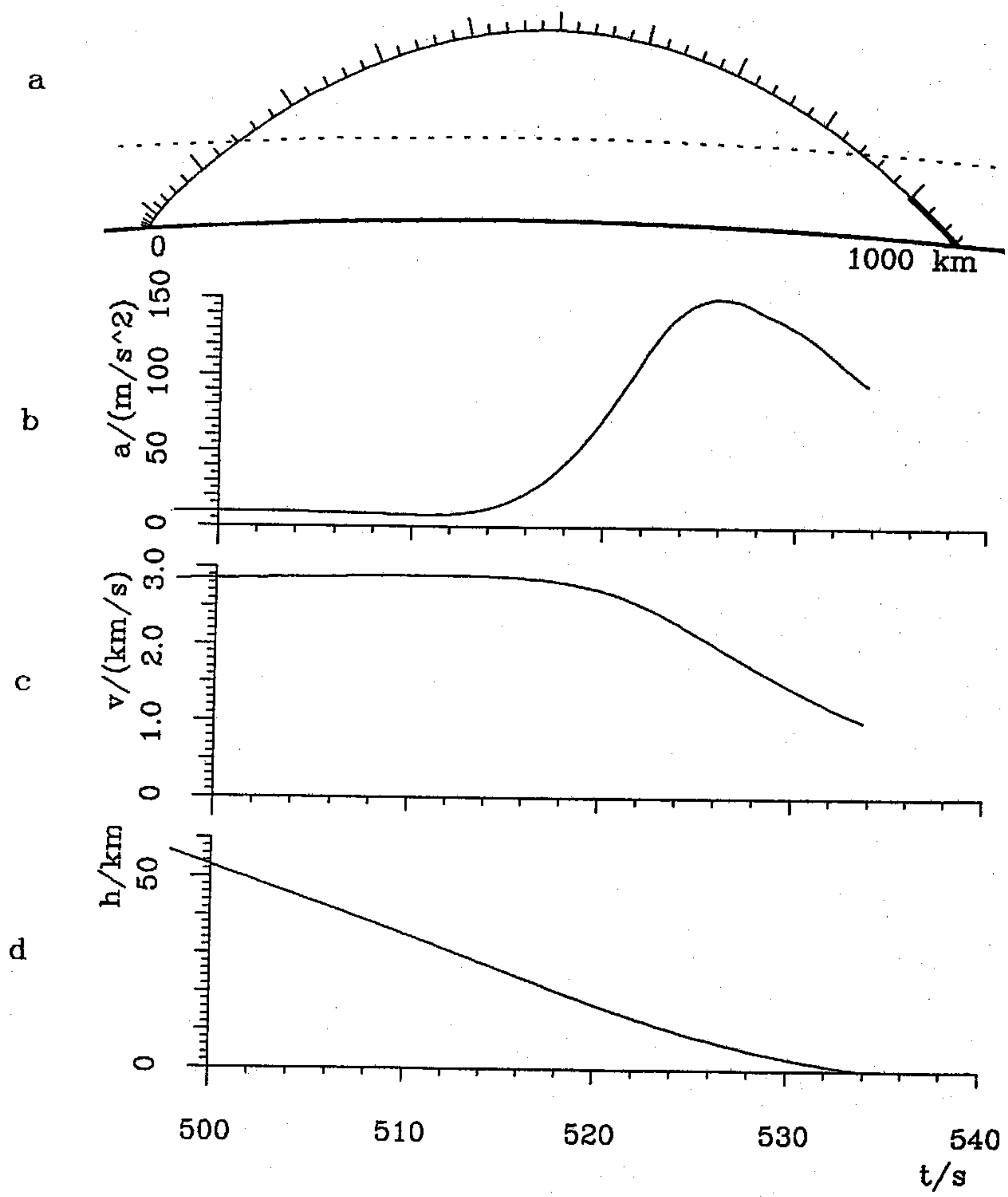

Fig. 3-3 Near minimum energy trajectory over 1,000 km range and reentry for a typical reentry vehicle (ballistic coefficient $\beta = 7{,}000\ kg/m^2$), computed with the program described in the Appendix.
a) Total trajectory. One tick corresponds to 10 seconds. The dotted line marks 100 km altitude. The reentry phase is indicated.
b) Deceleration a in m/s^2,
c) Velocity v in km/s,
d) Altitude h in km,
during reentry, versus time t after launch in seconds.

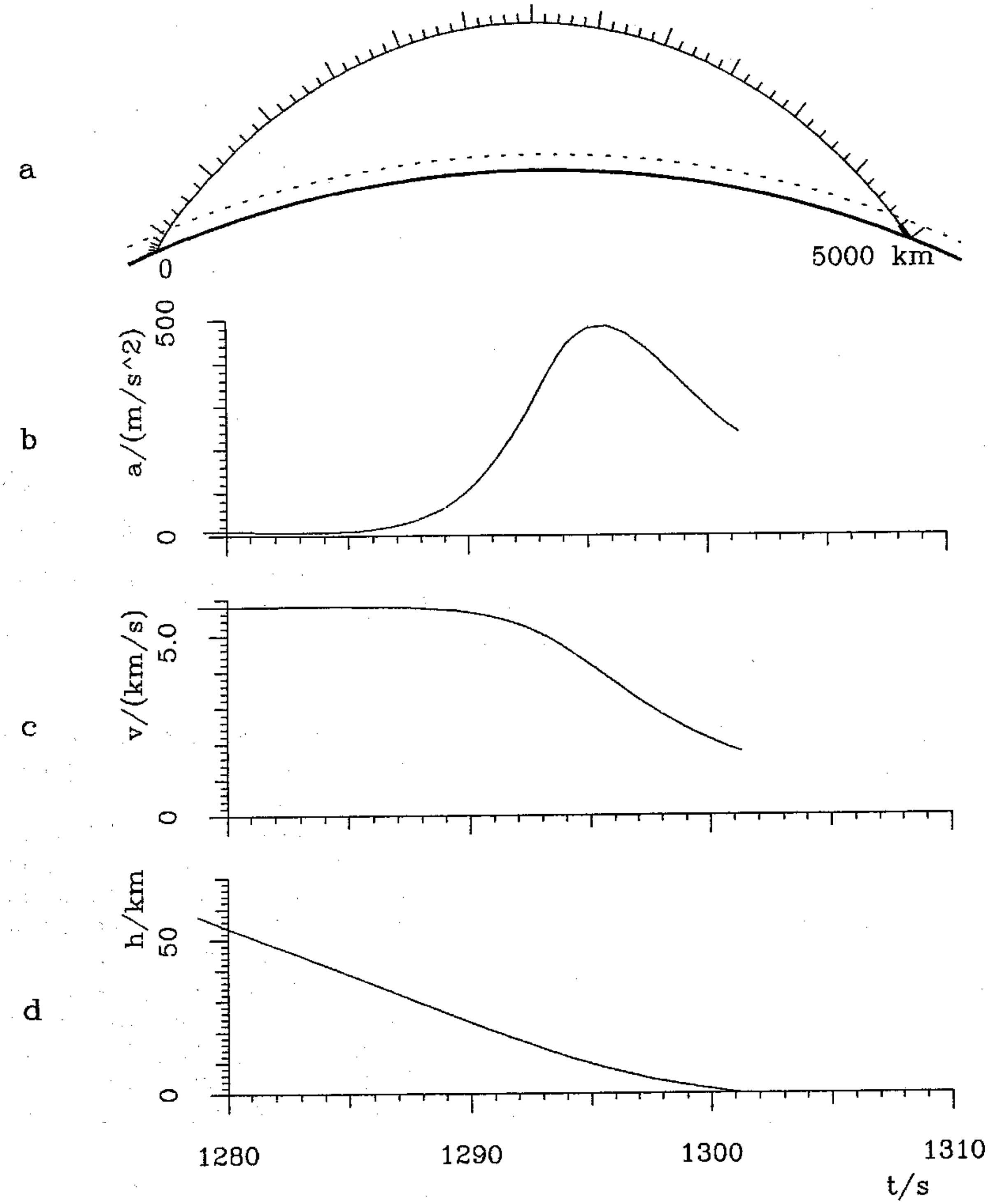

Fig. 3-4 Near minimum energy trajectory over 5,000 km range and reentry for a typical reentry vehicle (ballistic coefficient $\beta = 7{,}000$ kg/m^2), computed with the program described in the Appendix.
a) Total trajectory. One tick corresponds to 20 seconds. The dotted line marks 100 km altitude. The reentry phase is indicated.
b) Deceleration a in m/s^2,
c) Velocity v in km/s,
d) Altitude h in km,
during reentry, versus time t after launch in seconds.

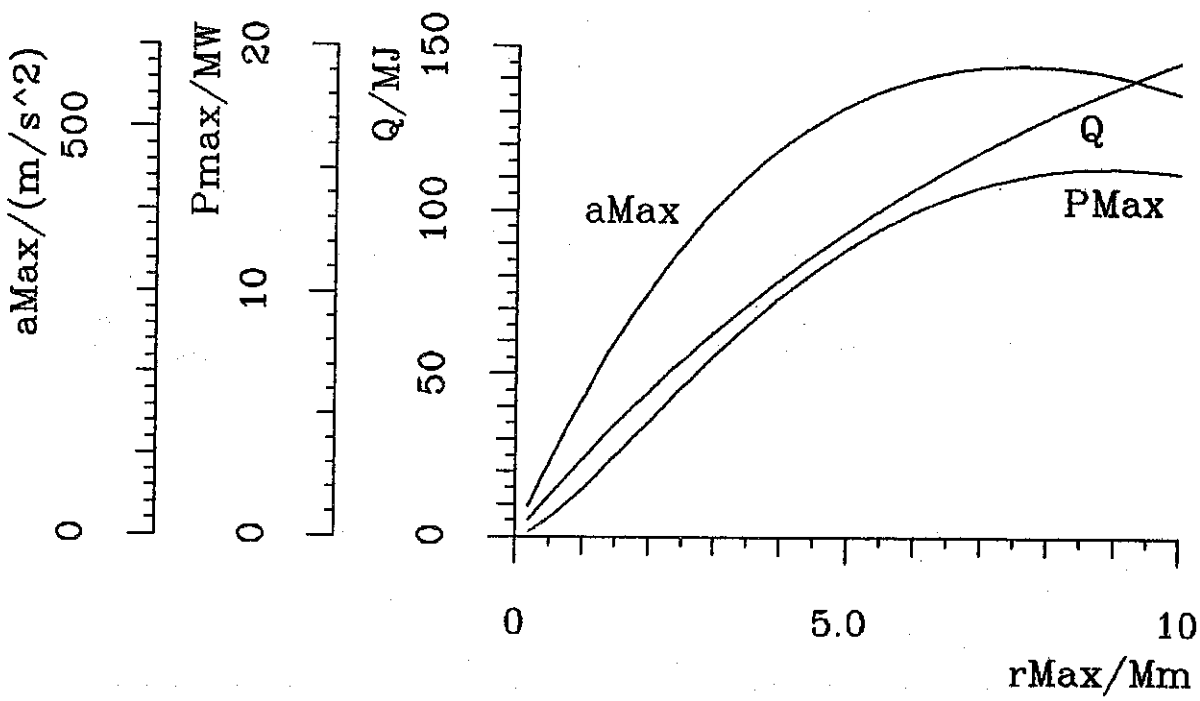

Fig. 3-5 Variation of maximum deceleration a_{max} in m/s^2, maximum heat influx P_{max} in megawatt, and total heat energy input Q in megajoule with range in megameter (= 1,000 km), for minimum energy trajectories and an exponential atmosphere (ballistic coefficient β = 7,000 kg/m^2, nose radius r_N = 0.04 m), according to (3-19), (3-23), and (3-26).

fiber with carbon or phenol are used;[9] using the specific energy for vaporization of carbon, 65 Megajoules per kilogram, one can gain an idea of the necessary thickness. For short and intermediate ranges, other materials may suffice (e.g., fused silica radomes).

As examples, Figs. 3-2 to 3-4 depict the trajectories and give the time courses of deceleration, velocity, and altitude for reentry vehicles which have flown near mimimum energy trajectories over 100, 1,000, and 5,000 km, as computed by the program described in the Appendix for a standard atmosphere. Fig. 3-5 shows the variation of maximum deceleration and of thermal properties with range for minimum energy trajectories and an exponential atmosphere. It shows that thermal problems are not very relevant for ranges below 1,000 km.

In reality, things are much more complicated; lift can be present, moments need to be included, ablation can alter the aerodynamic characteristics of the vehicle, radiation contributes to the thermal processes, chemical decomposition of the air can take place.[10] For an example of how a gliding reentry using lift can increase the range of a ballistic missile, see 6.1.2.3.

3.1.3 Typical total trajectories

Using the program described in the Appendix, total ballistic missile trajectories were computed for several maximum ranges from 100 to 10,000 km, using typical values for the missile parameters. Numerical results are given in Table 3-1. Fig. 3-6 shows the trajectories. The altitude 100 km has been marked as a rough margin of the atmosphere.

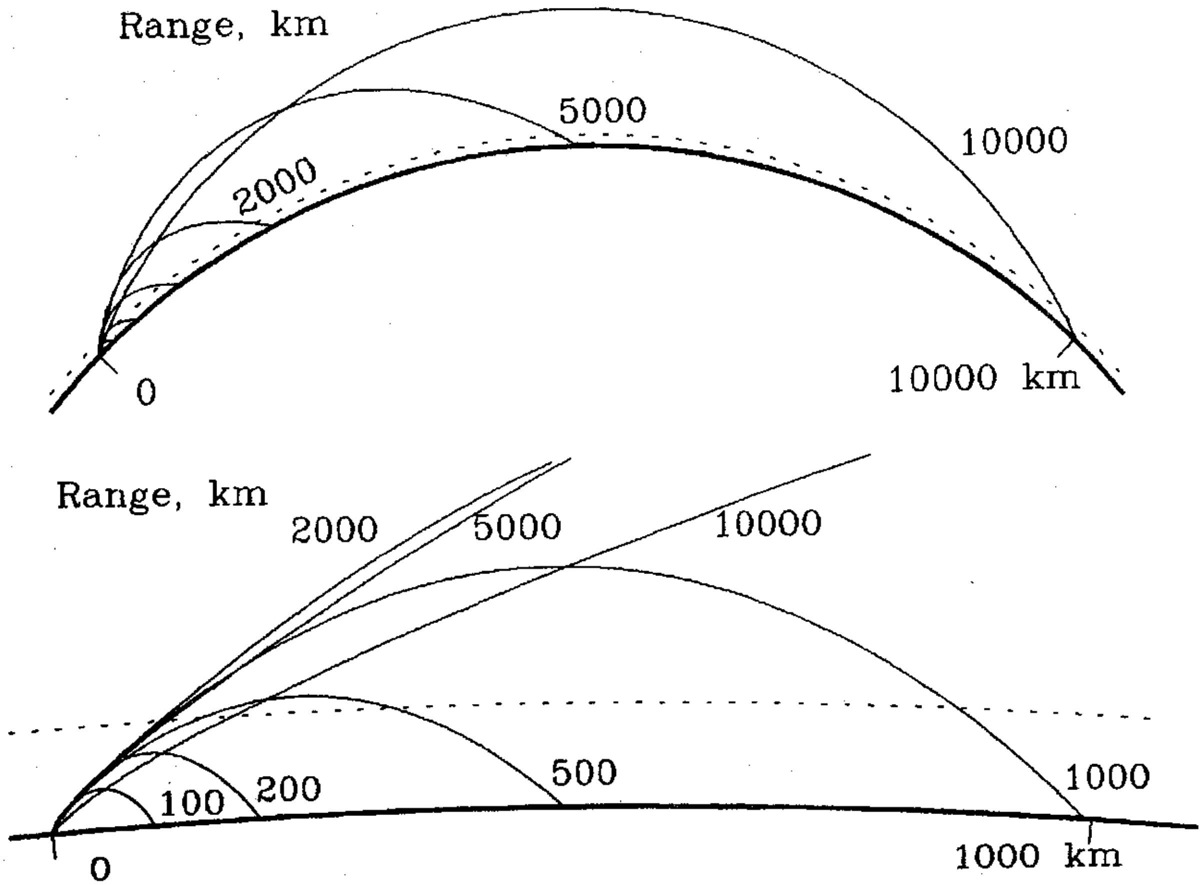

Fig. 3-6 Trajectories of ballistic missiles with 100 to 10,000 km maximum range as indicated, computed by the program described in the Appendix, drawn to two different scales. In order to give an idea of the atmosphere, the altitude 100 km is indicated. For numerical results see Table 3-1.

3.1.4 Lofting or Depressing of Trajectories

If the angle α_B between the velocity and the horizontal at burnout is lower than that for maximum range α_{Brmax}, the range and the flight time get shorter. If, conversely, the angle is higher, the range gets shorter whereas the flight time increases. Both variants could be used to increase the angular region from which the missile could approach its target, and which would have to be searched by a defense radar. Depressed trajectories, in addition, decrease the warning time, because the missile crosses the target's horizon later and the flight time is shorter. Lofting or depressing could be achieved by sacrificing range (which in many cases is no real sacrifice, because the target is at less than the maximum range), or by offloading payload (which could mean less reentry vehicles for MIRVed missiles, less explosive or less submunitions for conventional missiles). For a quantitative analysis, see 6.1.2.2.

3.2 Ballistic Missile Guidance and Targeting Accuracy

Whereas artillery rockets often have no guidance (aiming accuracy depends on the correct angular position of the launch tube, taking into account weather and other factors, as with normal artillery), early tactical ballistic missiles used simplified inertial guidance, augmented

Table 3-1 Parameters of realistic ballistic missile trajectories over maximum ranges from 100 km to 10,000 km (as depicted in Fig. 3-6). The values calculated correspond to near-minimum energy trajectories; deviations can arise from variations in missile and trajectory parameters. The thermal quantities have been computed for typical reentry vehicle properties and give only rough estimates. For 100 km range, the trajectory remains completely within the atmosphere; the reentry velocity given is a reasonable mean value for the terminal flight phase.

Range r, km	100	200	500	1,000	2,000	5,000	10,000
Typical no. of stages	1	1	1–2	2	2	2	3–4
Flight time T, min	3.5	5	7	9	13	22	33
Burnout:							
velocity v_B, km/s	1.0	1.3	2.0	2.8	3.9	5.5	6.9
angle α_B, deg	50	45	40	37	35	31	21
Ceiling h_{max}, km	40	70	120	230	450	900	1300
Duration at altitudes above 100 km, min	–	–	2	6	10	19	31
Duration at altitudes above 20 km, min	2	3	5	8	12	21	32
Reentry:							
Velocity v_R, km/s	(0.6)	1.1	1.8	2.8	4.0	5.8	7.2
Max.dec. a_{max}, m/s^2	(20)	40	80	150	280	490	480
Max. power P_{max}, MW	0.02	0.1	1	5	10	10	20
Heat energy Q, MJ	1	2	20	50	100	100	200

by radio command. Present ballistic missiles normally use full inertial guidance: the momentary vector sum of inertial and gravity forces relative to a fixed frame of reference is measured with gyroscopes and accelerometers. If the vector of gravity acceleration is known (e.g., by a model of the earth's gravitational field), it can be subtracted to yield the real acceleration. One- and twofold integration over time then allows calculation of the velocity and location vectors, respectively, provided the initial conditions are known. Since today's ballistic missiles (with the exception of the Pershing 2, see below) fly strictly ballistic trajectories after burnout without the possibility of correction, the trajectory is determined by the location and velocity vectors at burnout. This means that the guidance system works only during the boost phase, and, for missiles with multiple independently targetable reentry vehicles, also during the post-boost phase. Besides giving control commands to keep the missile on its intended trajectory, the most important task of the inertial guidance system, is to ensure that the missile flies through the correct point with the correct velocity, and then to shut off the motor with very high precision.

An error analysis for ballistic missile guidance has to take into account a wide variety of factors:[11]

- uncertainties in the launch point and target positions;
- uncertainties in the velocity of the launcher (this is no problem for tactical ballistic missiles, because the launcher has to be fixed with respect to the earth when firing);
- uncertainties in the initial alignment of the gyroscope platform;
- errors due to non-orthogonality of the accelerometers;
- errors in bias and scale factor of the accelerometers;
- gyroscope bias drift and acceleration-dependent drift;

- errors of thrust termination;
- errors of the gravitational model used;
- atmospheric variations during reentry;
- irregularities caused by asymmetric ablation of the reentry vehicle or by asymmetric transition to turbulent flow;
- errors of the fusing mechanism.

By using very sophisticated inertial guidance systems, modern U.S. ICBMs achieve a circular error probable (CEP, see 3.3.1) of 180 meter (Minuteman III) and 90 meter (MX), respectively; current Soviet ICBMs are credited with 200 – 280 m.[12] Because tactical ballistic missiles are less expensive than strategic ones, it is improbable that their inertial guidance systems are of the same high quality as those for strategic missiles. Therefore, the figures quoted for the circular error probable of modern Soviet tactical ballistic missiles (around 350 meters, see 3.4) seem technically sound.

If the expense and the problems which are connected with high quality inertial guidance systems were accepted, tactical ballistic missiles could theoretically achieve circular errors probable of about 50 m.[13] It is doubtful whether significant reductions below 50 m are possible using inertial guidance only. This would require additional correction signals which measure the position during later phases of flight. Such signals could be provided by stellar tracking during the free flight phase, by radio signals from navigation satellites, or by measuring features of the area around the target during reentry. In all cases, a capability to maneuver during reentry would be necessary (this could be done by variation of aerodynamic properties, e.g., control flaps). The first ballistic missile in the world to use terminal-phase target recognition and a maneuvering reentry vehicle (MaRV) is the U.S. intermediate-range Pershing 2. Here, after a deceleration maneuver using lift, the reentry vehicle takes radar images of the area below; guidance signals allow for a circular error probable of only 30 to 45 meters.[14] (The non-ballistic, air-breathing cruise missiles are able to measure their position by taking terrain altitude profiles several times during their flight. In this way, it is even possible to achieve a circular error probable of 20 meter or less.)

It cannot be ruled out that future Soviet tactical ballistic missiles will be equipped with a similar guidance system. For the generation being deployed presently, however, this can be ruled out with certainty. Therefore, sporadic public claims that the present SS-21, SS-23 and SS-12 mod. have accuracies of 30 meters have no technical foundation.[15]

If tactical ballistic missiles or their submunitions are to achieve even higher accuracies (e.g., to reliably hit buildings or even moving targets like tanks), circular errors probable of 1 – 2 meters would be necessary. This would require advance forms of target recognition such as infrared or millimeter-wave radar seekers. Although such systems are in the development stage for the 100 – 450 kilometer range ATACMS missile (see 3.4), significant technical hurdles exist for ballistic missiles of greater range. This holds because submunition release, and especially the seeking mechanisms, are much more difficult at the higher reentry velocities of those missiles.

3.3 Damage/Destruction Effects of Tactical Ballistic Missiles

3.3.1 General Relations for Calculation of Damage

3.3.1.1 Probability of Damage

For conventional as well as nuclear weapons, the destructive effects decrease with the distance from the center of explosion according to a known law. The peak overpressure in an explosion shock wave decays roughly by the inverse of the cubic power of the distance, the area density of fragments decreases by the inverse of the square of the distance, etc. Other effects follow more complicated laws (e.g., the radiation intensity,the velocity of fragments). Often, the amount of effect needed for damage to a target class is known (with some uncertainty, of course), and it is assumed that every target for which this threshold is exceeded is destroyed, while targets where the weapon effect remains below the threshold, stay intact. In this case, damage to a target is equivalent to its being at less than the so-called lethal distance r_L from the center. This distance can be determined using the effects-distance dependence. For surface nuclear explosions and targets hardened to more than 21 megapascal (300 psi) overpressure, e.g., the lethal distance is given by [16]

$$r_L = \left(\frac{Y}{H\,f(H)}\right)^{1/3}, \qquad (3\text{-}28)$$

where Y is the explosive yield and

$$f(H) = \left[\,3.0\cdot10^{-5}\frac{1}{H/\mathrm{kPa}} - 1.39\cdot10^{-5}\frac{1}{(H/\mathrm{kPa})^{1/2}} + 1.55\cdot10^{-6}\right]\frac{\mathrm{t\,TNT}}{\mathrm{m}^3\,\mathrm{kPa}} \qquad (3\text{-}29)$$

is a slowly varying function of the hardness H. If it is further assumed that the probability distribution of the actual weapons' impact points around the target is governed by a Gaussian function, the so-called probability of kill is

$$p_k = 1 - 0.5^{(r_L/\mathrm{CEP})^2}, \qquad (3\text{-}30)$$

where CEP, the "circular error probable", is the radius of a circle within which a weapon will land with probability 0.5. In order to calculate the functional probability of damage p_{dam} to the target, the kill probability has to be multiplied by several other probabilities:

$$p_{dam} = p_{pls}\, p_{pen}\, p_{rel}\, p_k. \qquad (3\text{-}31)$$

These are the probabilities of pre-launch survival p_{pls}, of penetration of defenses p_{pen}, and of reliable functioning from launch to warhead ignition p_{rel}. (For MIRVed missiles and employment of more than one weapon against one target, more complicated equations hold.[17])

3.3.1.2 Scaling Laws for Explosion Shock Waves

The transport of explosion energy through aerodynamic effects follows simple scaling laws which hold "from charges of a few grams of explosive to ... nuclear explosions in the many millions of tons".[18] For similar conditions, the distances for the same values of dynamic vari-

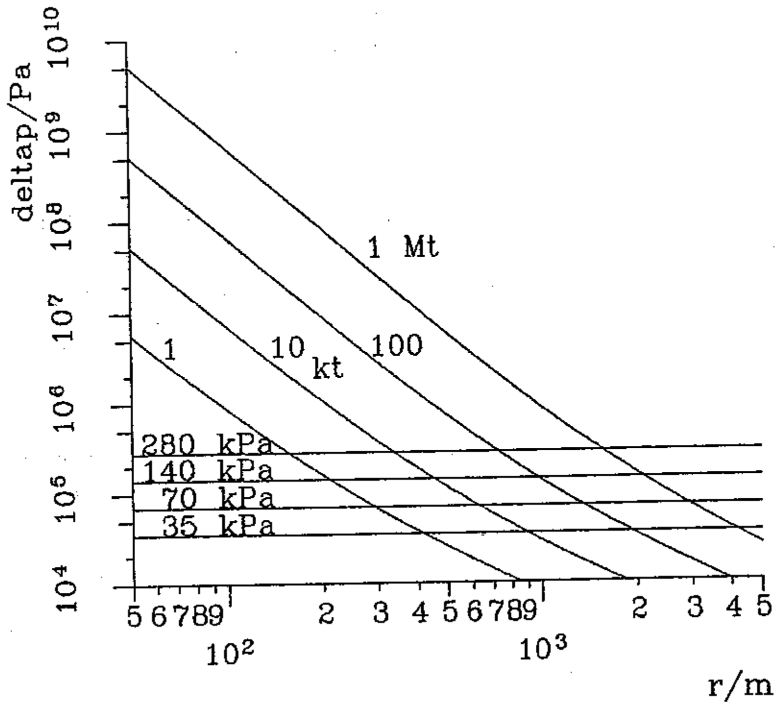

Fig. 3-7 Peak overpressure Δp in kilopascal versus distance r in meter from center, for nuclear explosions near the ground, after (3-33), for yields of 1, 10, 100 kiloton, and 1 megaton TNT. Both axes are in logarithmic scale. Typical values for damage to buildings (35 and 70 kPa), reinforced concrete structures (140 kPa) and hardened overground bunkers (280 kPa) are indicated.

ables scale with the cubic root of the explosive yield. If, e.g., the peak overpressure in the shock wave has a certain value for a yield Y_2 at the distance R_2, then the same overpressure value applies for the yield Y_1 at the distance R_1 given by:[19]

$$R_1 = R_2 \left(\frac{Y_1}{Y_2}\right)^{1/3} . \qquad (3\text{-}32)$$

The same scaling applies to the times when a dynamic variable takes a certain value. Even crater depths and radii scale approximately with the cubic root of the yield.[20]

3.3.2 Damage by Nuclear Explosions

3.3.2.1 Blast Overpressure

For a surface nuclear explosion of yield Y, the dependence of the peak overpressure Δp in the shock wave, on the distance r from the center can be approximated by[21]

$$\Delta p = 6.4 \cdot 10^5 \frac{\text{kPa m}^3}{\text{t TNT}} \frac{Y}{r^3} + 7.0 \cdot 10^3 \frac{\text{kPa m}^{3/2}}{(\text{t TNT})^{1/2}} \left(\frac{Y}{r^3}\right)^{1/2} , \qquad (3\text{-}33)$$

where the units of the empirical constants contain kilopascal (air pressure at sea level is 101 kPa; in U.S. units, 1 psi = 6.895 kPa), meter, and ton TNT (1 t TNT equals 4.2 gigajoule energy). (Air blasts are lower by about a factor of 2; for the overpressure equation in free air, see (4-54) in section 4.3.4.1.) Fig. 3-7 shows this relation for different yields. Overground objects will additionally be affected by the dynamic pressure p_d of the winds associated with the shock wave which can be derived from the peak overpressure Δp by [22]

$$p_d = \frac{2.5 \, \Delta p^2}{7 \, p_a + \Delta p} \tag{3-34}$$

(p_a: ambient pressure). For peak overpressures up to 4.7 times the ambient pressure (i.e. 470 kilopascal at sea level), the dynamic pressure is lower than the peak overpressure. For large peak overpressures, the dynamic pressure approaches 2.5 times the peak overpressure. Overpressure values which cause specific damages are listed in Table 3-2, some are indicated in Fig. 3-7, too.

Table 3-2 Values of peak overpressure Δp for specific damages.[23] Note that damage to humans will occur by indirect effects at lower values (flying glass particles, collapse of buildings etc.).

Damage	Overpressure in Kilopascal	(in psi)
Light housing destroyed	35	5
Brick housing/commercial buildings destroyed	70	10
Reinforced concrete structures destroyed	140	20
Severe lung damage/eardrum rupture in humans	150 – 200	20 – 30
Death of humans	300 – 700	40 – 100
Shallow buried structures destroyed	300 – 2,000	45 – 280
Hardened ICBM silo destroyed	100,000 – 170,000	1,500 – 2,500

Potential military targets of tactical ballistic missiles in Europe are mostly above ground (airfields, air defense sites), hardened by concrete, or are protected by layers of soil (nuclear storage sites). This means that they will certainly be destroyed if the overpressure is above 140 kPa; for a typical explosive yield of a nuclear tactical ballistic missile of 100 kiloton TNT, such installations would be destroyed in a circle of about 0.7 km radius (see Fig. 3-7). Only the relatively small number of most important command and control centers may be hardened to a greater degree; it is, however, improbable that an overpressure value like that required for the destruction of ICBM silos is achieved. Given sufficient accuracy, nuclear tactical ballistic missiles could successfully attack underground command bunkers. In order to be able to attack underground structures more effectively, the U.S. is developing an earth-penetrating warhead which explodes only after it has come to a stop some 20 meters underground.[24]

3.3.2.2 *Other Effects of Nuclear Explosions*

Whereas for damage to military facilities overpressure is the most important characteristic, urban and agricultural areas are in addition affected by other effects, especially heat and nuclear radiation. For the range of yields which could be carried by tactical ballistic missiles, 1

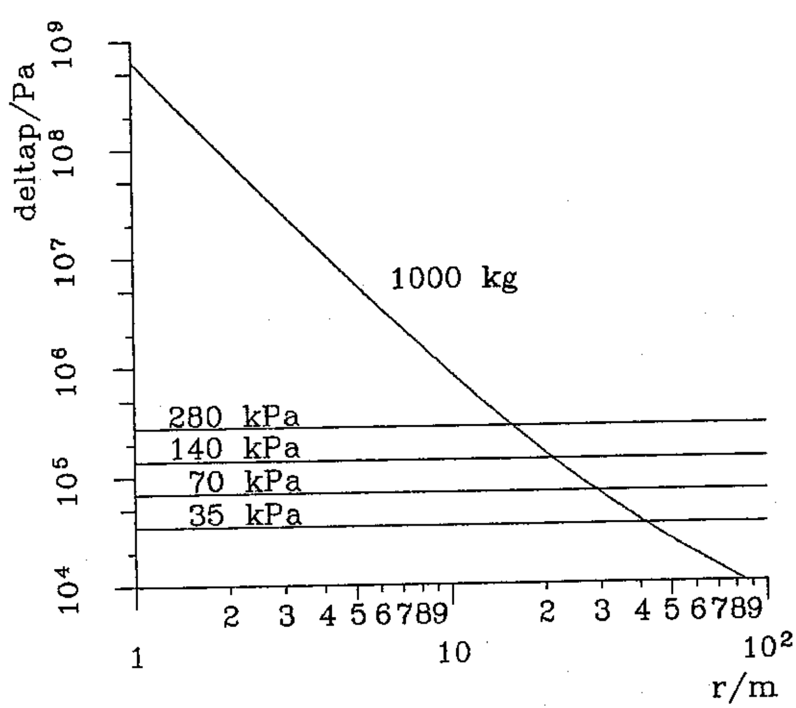

Fig. 3-8 Peak overpressure Δp of shock wave of conventional explosion of yield $Y = 1{,}000$ kg TNT, versus distance r from center. Both axes are in logarithmic scale. Values for other yields can be derived by cube-root scaling after (3-32). The same damage overpressures as in Fig. 3-7 are indicated.

kiloton up to 1 megaton TNT, the areas of lethal damage by the three main effects vary from 1.5 to 390 km^2.[25] For cities of 4 million inhabitants, one 1 Mt explosion or 10 explosions of 40 kt each would mean 500,000 to 1 million deaths and 600,000 to 1 million injuries.[26] For a "limited nuclear war", use of less than 200 explosions of 200 kt TNT each, directed only against military targets in East and West Germany, would result in 2 to 10 million deaths and 7 to 25 million injuries (out of a total population of about 80 million).[27]

3.3.3 Tactical Ballistic Missiles with Conventional Warheads

3.3.3.1 Unitary Explosive Warhead

For a conventional explosive, the yield is smaller by approximately a factor of 10^5 than that of a nuclear explosive of comparable mass. Using cubic root scaling, the distances from the center for equal amounts of overpressure, i.e., equal damage, are smaller by a factor of about 40. This is confirmed if the empirical relation for the shock wave overpressure for conventional explosions,[28]

$$\Delta p = 808\, p_0 \frac{1 + \left(\frac{r_{sc}}{4.5\,\mathrm{m}}\right)^2}{\left(\left(1 + \left(\frac{r_{sc}}{0.048\,\mathrm{m}}\right)^2\right)\left(1 + \left(\frac{r_{sc}}{0.32\,\mathrm{m}}\right)^2\right)\left(1 + \left(\frac{r_{sc}}{1.35\,\mathrm{m}}\right)^2\right)\right)^{1/2}}, \quad (3\text{-}35)$$

is plotted versus the distance r (Fig. 3-8). Here the so-called scaled distance r_{sc} contains correction factors for ambient air density ρ and explosive yield Y:

$$r_{sc} = r\left(\frac{\rho}{\rho_0}\frac{1\,\mathrm{kg\,TNT}}{Y}\right)^{1/3} . \qquad (3\text{-}36)$$

Table 3-3 gives a list of damage overpressures for potential targets of conventional tactical ballistic missiles. These values (and those of Table 3-2), together with the overpressure dependence of Fig. 3-8, give damage distances from the explosion. For a 1,000 kg warhead, e.g., a radar is damaged, if it is less than 30 – 50 meter away; a semi-hard overground structure remains intact if the explosion occurs at more than 20 meters distance.

Table 3-3 Damage overpressures for several military objects which could be targets of conventional tactical ballistic missiles.[29]

Object	Damage Overpressure in kPa
Parked aircraft	5 – 20
Air defense radar, truck, missile launcher	35 – 70
Reinforced concrete structure (aircraft shelter, command bunker)	280

3.3.3.2 Other Warhead Types: Shrapnel, Shape Charge, Fuel-Air Explosive [30]

In order to enhance the damage effects to hard objects, a conventional explosive is sometimes surrounded by metallic pieces which are highly accelerated by the expanding gases and may penetrate light armor. These fragments have typical masses from 5 to 100 grams. For a given payload of a ballistic missile, added metal mass has to be compensated for by reduced explosive mass. If 500 kg shrapnel surround 500 kg explosive and are distributed in 50 gram pieces, 10,000 pieces will be produced in total. Since these cover the surface of an expanding sphere, their area density will decrease by the square of the distance. At 28 m distance, only 1 piece per m^2 is expected; at 50 m, one piece will hit every 3 m^2. The formula for the initial fragment velocity will be given in section 4.3.1. Since beyond 50 m the velocity may have decreased by one third, to values around 1 km/s, damage to armored vehicles is at the least uncertain, and reinforced concrete structures will remain intact. This means that fragmentation warheads do not result in greater damage areas than pure explosive warheads.

If the conventional explosive is formed as a shape charge with a conical metal liner, a very fast jet of metal and hot gases is produced which has a velocity of 8 – 9 km/s at its tip and 1 km/s at its tail. This jet exerts pressures of about 3 gigapascal, and can even penetrate heavy armor. Typical penetration depths are 3 cone diameters in steel, and 8 to 10 cone diameters in concrete.[31] Thus, using 1,000 kg of explosive, about 3 meter of steel or 10 meter of concrete could be penetrated. Since the jet is localized to significantly less than 1 meter, the target would have to be hit exactly, which is not easy to achieve. Moreover, the arrival angle of ballistic missiles would increase the length of material, bunkers could be subdivided to confine the damage, and several meters of soil would cause an early ignition. Thus, a shape charge is of no great use for attacks with tactical ballistic missiles.

A final alternative would be to spread a fuel-air explosive and ignite it with delay. This could cover a significantly larger area, but at the expense of reduced overpressure. Besides the technical difficulties of dispersal from a container moving with several times the velocity of sound, this concept would be effective only against personnel and other "soft" targets, but not against reinforced concrete structures or underground bunkers. So, it is unlikely that ballistic missiles for attacks against military targets will carry fuel-air explosives.

3.3.3.3 Conventional Ballistic Missiles equipped with Submunitions

It would make much more sense from a military point of view to equip tactical ballistic missiles with submunitions. These could be of several types (simple explosives, fragmentation, shape charge, etc.) and could be designed for specific purposes (e.g., penetration of a runway and explosion from underneath).[32] To take an example, there have been reports that a conventional Pershing 2 missile could be equipped with several dozen submunitions; radar correlation would guide the maneuvering reentry vehicle to a runway, and submunitions would be released by rotation. These would penetrate the runway on account of their kinetic energy before exploding.[33] For short-range ballistic missiles (MLRS with a range of 18 km, ATACMS with ranges of 100 – 450 km) plans exist to develop submunitions with homing sensors which seek tanks, self-propelled artillery and the like, including tactical missile launchers.[34]

Using submunitions, the damaging effects could be distributed to distances from the impact point, typically larger by a factor of two than with a single warhead.[35] Tradeoffs according to the number of submunitions and the dispersal radius have to be taken into account.

Use of homing submunitions on ballistic missiles with ranges of more than several 100 km is not without problems. As Table 3-1 suggests, the reentry thermal load starts to be significant at 2 to 3 km/s reentry velocity (500 to 1,000 km range). Providing each submunition with an individual heat shield would be complicated and would involve reducing the weapon payload. Difficulties would increase further, if protective shields had to be integrated with active seeking mechanisms like infrared sensors or millimeter-wave seekers. For several years to come, sensor-carrying submunitions will only be released after the reentry vehicle has decelerated to less than 1 – 2 km/s, i.e., below 10 km altitude for normal ballistic trajectories (see Figs. 3-3, 3-4), leaving little capability for lateral maneuvers. Because of size, mass, and power limits, the target detection range of the seeking mechanism of a submunition will be limited. With a downward path, each submunition will fly in the direction toward a potential target, and will be able to acquire it only shortly before a possible impact. Targets several hundreds of meters away from the ballistic impact point could escape detection; therefore, many submunitions may fail to hit a target object.

One should note that aircraft, cruise and stand-off missiles do not have this restriction. They can fly at a constant altitude, can easily change their flight path, and can utilize a larger and more capable detection system. They could e.g., search along a meander pattern and release homing submunitions as targets are detected. Alternatively, they could fly along some ground feature (e.g., a runway) dispensing submunitions along their way. Therefore it seems that ballistic missiles of any range have significant disadvantages compared to other delivery systems, if submunitions are to be dispensed in a specific pattern or in such a way that independent movement and homing is possible. Target seeking submunitions could be dispensed somewhat more effectively from ballistic missiles if a gliding reentry using lift were first to strongly decelerate the vehicle and change its trajectory to a quasi-aerodynamic one for a short period, see 6.1.2.3. Whereas a first step in this direction has been taken with the U.S. Pershing 2 missile, such a capability would require completely new reentry vehicle designs, and aerodynamic vehicles would in any case remain more versatile for that purpose.

3.3.3.4 *Tactical Ballistic Missiles with Chemical or Biological Warheads*

Similarly to artillery rockets, short-range ballistic missiles could be equipped with warheads dispensing chemical or biological agents, shortly before or after impact. Because of the higher reentry velocities, using such agents with longer-range missiles (from 500 km upwards) may necessitate the development of new dispensing mechanisms. In addition, new kinds of submunitions would probably be required if distribution over a certain area is wanted. It seems improbable that tactical ballistic missiles will, in the foreseeable future, be able to distribute chemical or biological weapons in a planned, not random pattern. Whereas aerodynamic vehicles with terrain recognition guidance, are not only able to distribute chemical or biological weapons or submunitions in a planned fashion, they can even measure the local wind conditions found on arrival at the target, and adapt the distribution pattern accordingly. Thus, ballistic missiles of all ranges are likely to remain inferior (from a military point of view) to air-breathing cruise and stand-off missiles for the next decade and longer.[36]

3.4 Existing or Planned Tactical Ballistic Missile Systems

Properties of existing tactical ballistic missiles (i.e., with ranges between 70 and 5,500 km) have been compiled from various sources in Table 3-4. Most of the data are not officially confirmed by the owner state; for a comprehensive picture on the data and their variations, the reader should consult the sources given. Table 3-5 lists some missile types which have been discussed or are known to be in the development process at present. Land-based missiles between 500 and 5,500 km range of the USA and the USSR will be destroyed according to the INF Treaty, and both countries may not field new types of land-based missiles having such ranges. Therefore, some of the types mentioned as being in the planning stage are banned from being completely developed and deployed.

Non-nuclear tactical ballistic missiles above 70 km range have been exported to several countries outside of the WTO by the USSR:[37]

- Egypt: FROG-7 (70 km range), Scud-B (300 km)
- Iraq: FROG-7, Scud-B, SS-21 (120 km)
- Libya: FROG-7, Scud-B
- North Korea: FROG-7
- Syria: FROG-7, Scud-B, SS-21.

According to Israelian sources, Iraq has developed (possibly with other countries) ballistic missiles of 650 km range.[38]

The following countries have received tactical ballistic missiles from the USA and/or have developed upgraded missiles with more than 100 km range as adaptations, or on their own:[39]

- Israel has indigenously developed the Jericho and Jericho II missiles (450 and 500-800 km range).

Table 3-4 (next page) Existing ballistic missiles with ranges between 70 and 5,500 km, compiled from various sources.[40] Note that most data are not officially confirmed by the corresponding state (except for data exchanged under an arms limitation treaty). Particularly uncertain are the values of the targeting accuracy (circular error probable). For the characteristics of several missiles, differing numbers can be found in the literature (see the sources given).

Type	Country	First Deployment	Deployment Type	No. of Stages	Fuel Type	Max. Range, km	Launch Mass, Mg	Total Length, m	Body Diameter, m	Payload, Mg	Max. No. of Warheads	Warhead Type(s)	Nuclear Yield, kt TNT	Circular Error Probable, m	Remarks
Land-Based Ballistic Missiles															
Pluton	F	1974	mobile	1	solid	120	2.423	7.65	0.65	..	1	N	15 or 25	150-300	
SSBS S-3	F	1980	silo	2	solid	3500	25.82	13.9	1.5	..	1	N	1200	150-300	
DF 2/CSS-1	PRC	1970	mobile	1	liquid	1200	26	21	1.6	1	1	N	15-20	..	
DF 3/CSS-2	PRC	1970	silo	1	liquid	2700	27	20.62	2.46	..	1	N	1000-3000	..	2 stage model with 3 * 100 kt in development
Lance	USA	1972	mobile	1	stor.l.	110	1.10	6.14	0.56	0.23	1	N, HE	1-100	150-400	
Pershing 1A	USA/D	1962	mobile	2	solid	720	4.54	10.55	1.02	0.37	1	N	60-400	400	
Pershing 1B	USA	..	..	1	solid	..	..	8.13	1.02	..	1	..	..	..	
Pershing 2	USA	1983	mobile	2	solid	1800	7.26	10.61	1.02	1.40	1	N	5-50	40	MaRV
FROG-7	USSR	1965	mobile	1	solid	70	2.3	9.1	0.55	0.45	1	N,HE	200	400	
SS-21	USSR	1978	mobile	1	solid	120	3.0	6.0	0.85	0.45	1	N,HE,C	100	300	
Scud-B/SS-1c	USSR	1965	mobile	1	stor.l.	300	6.3	11.2	0.8	1.2	1	N,HE	1-500?	1000	also: Scud A (130 km), Scud C (450 km)
OTR-23/SS-23	USSR	1979/80	mobile	1	solid	500	10.0	7.52	0.97	0.65	1	N,HE,C	100	350	
OTR-22/SS-12 mod	USSR	1979	mobile	2	solid	900	..	12.38	1.01	0.45	1	N,HE,C	1000	300	
R-12/SS-4	USSR	1959	silo	1	liquid	2000	27	22.77	1.65	1.4	1	N,HE	1000	2400	
R-14/SS-5	USSR	1961	silo	1	liquid	3500	80	24.30	2.40	1.6	1	N	1000	1100	
RSD-10/SS-20	USSR	1977	mobile	2	solid	5000	25	16.49	1.79	0.7	3	N	150	400	also mod 1 with 1 RV of 1 Mt
Submarine-Based Ballistic Missiles															
MSBS M-20	F	1977	sub	2	solid	3000	20.03	10.7	1.5	..	1	N	1200	..	
MSBS M-4	F	1985	sub	3	solid	4500	35.03	11.0	1.9	..	6	N	150	..	
Polaris A-3	GB/USA	1967	sub	2	solid	4600	16	9.85	1.37	0.7	3	N	200	900	
JL-1/CSS-N-3	PRC	1983/4	sub	..	solid	2800	13.8	10	1.5	..	1	N	2000	..	
Poseidon C-3	USA	1971	sub	2	solid	4000	29	10.4	1.9	1.5	10	N	40	450	
SS-N-5	USSR	1964	sub	2	stor.l.?	1400	18	13	1.4	1.25	1	N	1000	2800	
SS-N-6	USSR	1968	sub	2	stor.l.	2400	19	10	1.6	0.7	1	N	500-1000	1300	mod 3: 3000 km range
SS-N-17	USSR	1977	sub	2	solid	3900	..	10	..	1.1	1	N	500	1400	

- South Korea has apparently adapted the "Korean SSM" from the U.S. Nike-Hercules missile (which itself is listed with 140 km range).
- Taiwan has produced the Ching Feng (Green Bee) which is similar to the U.S. Lance (Lance has a 110 km range).

Brazil has a multiple rocket launcher system. The largest rocket, X-40 (or SS-60), has 0.30 m diameter and one stage; it carries a 150 kg warhead over 65-68 km.[41]

The People's Republic of China has exported the CSS-2 intermediate-range ballistic missile (2,700 km range) to Saudi-Arabia.[42]

Countries having space-launch rockets have an inherent capability to transport payloads to ground targets. The following countries (besides the nuclear weapons states) are engaged in civilian space programs (for some, military connections are evident):[43]

- Argentina has the Condor (400 kg payload to 100 km altitude) under development.
- Brazil has the Sonda IV with 500 kg payload operational; VLS is planned.
- The (West) European Space Agency can transport payloads from 2 to 3 metric tons to orbit using the Ariane-2, -3 and -4 vehicles.
- India has the SLV-3 with 40 kg payload operational; ASLV, PSLV and GSLV are planned.
- Japan has four carriers (N-2, H-1A, H-2 and Mu-3S-2) capable of lifting 1 to 3 metric tons to orbit.
- Pakistan is reported to plan development of a space launch vehicle.
- Israel has launched a first observation satellite, using a "Comet" launcher believed to be based on the Jericho missiles.

Table 3-5 Some tactical ballistic missiles which have been proposed or are being developed.[44]

Hadès (France): mobile, 1 stage, solid fuel, 350-500 km range, 1 warhead, nuclear, to be deployed from 1992 on; range increase discussed after INF Treaty.
ATACMS (USA): mobile, 1 stage, solid fuel, 200-450 km range, warhead nuclear / chemical / conventional high energy / conventional homing submunition, to be deployed in early nineties; based on mod. Lance or Patriot; range increase discussed after INF Treaty.
CAM (USA): mobile, 1-2 stages, solid fuel, 800-1,000 km range, length about 10 m, payload 1,900 or 550 kg, warhead: submunitions, could use Pershing stages and radar correlation guidance, 30-45 m CEP – banned by INF Treaty.
BOSS/Axe (USA): 1 stage, solid fuel, 650 km range, 27.7 t launch mass, 14.6 m length, 1.9 m diameter, 6.4 t payload, gliding reentry, warhead: submunitions (348 kinetic energy penetrators for runway attack), CEP 30-45 m, motor: first stage of Trident C-4 SLBM – banned by INF Treaty.
TABAS (USA): 25 t payload, submunitions, would resemble Saturn rocket (complete Saturn V was about 100 m long and had 13 m diameter) – banned by INF Treaty.
SS-NX-13 (USSR): submarine-launched, 2 stages, 180-1,000 km range, 1 warhead, nuclear, radar homing guidance, for anti-ship attack, not yet operational.

Notes and References to Chapter 3:

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7 See note 6.

8 Loh (note 4), p. 183 f.

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10 For a detailed discussion, see: Regan (note 1), Loh (note 4).

11 Bunn/Tsipis (note 5).

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17 Tsipis (note 16), p. 308; M. Kreck, Eine ganz neue Entwicklung – Vergleich der Erstschlagsfähigkeit von Pershing 2 und SS-20 aus mathematischer Sicht, in: H.–P. Dürr et al. (Eds.), Verantwortung für den Frieden – Naturwissenschaftler gegen Atomrüstung, Reinbek: Rowohlt, 1983, p. 103.

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19 Brode (note 18), p. 192; Tsipis (note 16), p. 286.

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