6. Countermeasures – Efficiency – Cost Effectiveness

In order to arrive at an estimate of the efficiency with which future anti-tactical ballistic missile defense systems could intercept their targets, one has to look at possible countermeasures which could negate or at least reduce their impact, of course including counter-countermeasures of the defense. This is done in 6.1. Taking into account more general experiences and estimates concerning air defense on the one hand, and strategic ballistic missile defense on the other hand, 6.2 tries to convey an idea of the possible efficiency of anti-tactical ballistic missile defense systems. Section 6.3 argues relative costs of defense and offense.

6.1 Countermeasures against Anti-Tactical Ballistic Missile Defense Systems, and Counter-Countermeasures

Countermeasures which could be taken by a side wishing that its military goals of producing damage or destruction at specific targets could still be effected with sufficiently high probability despite missile defense systems, could loosely be categorized as passive, active, or offensive.

6.1.1 Passive Countermeasures

Passive measures would e.g. try to reduce the signatures used for the detection of ballistic missiles, or to protect them against the damaging effects of the defense weapons.

Whereas the first category could start at the boost phase (e.g. by screening part of the exhaust flame), its main impact would be in case of radar search systems. Radar cross sections of reentry vehicles could be reduced by sharpening the nose tips, rounding the backward edges, and using radar-absorbing material at the surface. As was demonstrated in 4.1.1.2, cross sections for ballistic missiles with ranges of 2,000 km and lower could be as low as 0.0003 m^2. Against such objects, the radar search detection range would decrease by a factor of about 3 (the third root of the cross section ratio) from those which apply in the case of present intercontinental ballistic missile reentry vehicles (with cross sections of about 0.01 m^2). For the numerical example of 4.1.1.3, a Patriot-class mobile radar searching in a 90 by 50 degrees solid angle, would detect an object from 1,000 km range, i.e. arriving with 2.8 km/s velocity, not in 85 km, but in 26 km distance – i.e. not 30, but only 10 seconds before its possible impact at the defense location. Accordingly, against such an object, the footprint boundary in the forward direction would be reduced from 5 km to 0.1 km (i.e., even self-defense becomes questionable). If the power-aperture product of the radar system were increased by a factor of 2, which seems to be near the limit for mobile systems, the reduction in detection distance – as compared with the Patriot-type radar – would still amount to a factor of 2.5. For several ballistic missile ranges and three values of the radar cross section, the search detection ranges as well as the forward boundaries of the defense footprint have been

Table 6-1 Search detection ranges R_{DetS} and forward boundaries of the defense footprint R_{FF} of a Type 1 ballistic missile defense system, against reentry vehicles of different radar cross sections σ, and different reentry velocities v_E, i.e. from different ballistic missile ranges r. The search detection range was computed after (4-11) and (4-13). Parameters used: $P_{av} = 10$ kW; $A_{eff} = 4.5$ m^2; $T_0 = 290$ K; $F_n = 3$; $F_L = 5$; $\Omega = 0.94$ sterad; $Q_i = 0.9$; $\delta = 0.042$; $\rho = 0.155$. (For missiles with more than 2,000 km range launched from known deployment regions, the azimuth range and thus the search solid angle could be smaller. The same value is chosen for all missile ranges, however, because a defense would have to search for missiles of all ranges.) The forward footprint boundary was computed by the procedure given in 5.1.2 with the program described in the Appendix; the interceptor characteristics of the Type 1 defense system are comparable to those of the Patriot missile, with modifications for trajectory control over the whole flight duration (for the parameters, see 5.1.5.1). A minimum interception altitude of $h_{min} = 2$ km was assumed. The reentry velocities have been taken from Table 3-1; for 200 km range at detection time, a somewhat lower value containing an angular correction is used. The defense could counteract to some extent by increasing its radar power-aperture product and the interceptor velocity. Note that the detection ranges assume optimization of the radar search frame time for the respective velocities; simultaneous optimization for all ranges is actually not possible.

Range r, km	100	200	500	1,000	2,000	5,000
Velocity v_E, km/s	0.6	0.8	1.8	2.8	4.0	5.8
Radar Cross Section $\sigma = 0.01$ m^2 (ICBM reentry vehicle of today)						
Search Detection Range R_{DetS}, km	142	129	99	85	76	67
Forward Footprint Boundary R_{FF}, km	80	57	30	21	13	2
Radar Cross Section $\sigma = 0.001$ m^2 (Intermediate value)						
Search Detection Range R_{DetS}, km	66	60	46	40	35	31
Forward Footprint Boundary R_{FF}, km	38	32	15	5	–	–
Radar Cross Section $\sigma = 0.0003$ m^2 (Theoretical limit for tactical ballistic missile with 2,000 km range or below)						
Search Detection Range R_{DetS}, km	44	40	31	26	24	(21)*)
Forward Footprint Boundary R_{FF}, km	27	25	7	0.1	–	–

*) At this reentry velocity, the nose tip has to be not as sharp, so that this cross section value will not be attainable here.

computed. Table 6-1 lists the results. Of course, in order to realize such a low radar cross section, payloads have to be separated from the missiles after burnout, which up to now is not done with one-stage (i.e., short-range) missiles. Converting such missiles having up to 500 km range to types which separate the warhead(s) will present some problems, e.g. for the guidance, but transfer of experiences and technology from missiles of greater range should not prove overly difficult. If in the aftermath of the INF Treaty ballistic missiles below 500 km would gain major importance, newer types would probably employ warhead separation in order to prepare for possible defense deployments.

As to passive protection against the defensive weapons effects, some additional amount of fragment stopping layers may be used, but this would only be effective if few fragments of already reduced velocity would hit. Against laser beam weapons during the boost phase, a significant amount of protection is possible by thermal protective layers and by missile rotation. Reentry vehicles of missiles of larger ranges already possess an effective thermal protective shield; this could without much difficulty be extended to shorter ranges.

6.1.2 Active Countermeasures

In the field of active countermeasures, a large number of actions could be taken comprising quantitative as well as qualitative changes.

6.1.2.1 Saturation, Change to Aerodynamic Missiles

The first possibility is to increase the number of tactical ballistic missiles, in order to saturate the defense. Success then may depend on the cost-exchange ratio between offense and defense (see 6.3).

Another possibility is to use cruise and stand-off missiles instead. This could be effective, because the operational characteristics of defense systems directed against ballistic, as opposed to aerodynamic, missiles are sufficiently different. In addition, for several military tasks requiring high accuracy and/or a special submunition distribution pattern, aerodynamic missiles are inherently more appropriate. The flight times would be longer than those of ballistic missiles, but most worst-case scenarios of surprise attack using tactical ballistic missiles could equally well be conceived using aerodynamic missiles launched from forward positions.

6.1.2.2 Lofting or Depressing of Trajectories

Without any change of hardware, existing ballistic missiles could be launched along trajectories at other than optimum elevation angles, as long as the target is not exactly at the maximum range of the missile. This will be the case in many tactical situations, and the variation in elevation angle is larger than could be for equal relative range variation in the case of intercontinental ballistic missiles. Lofted trajectories would have longer flight times, but would force search radars to illuminate larger solid angles. Depressed trajectories would add to this effect, would decrease the flight time, and, for longer ranges, would delay the time when the missile would rise above the radar horizon. Moreover, the time span when the missile or reentry vehicle were accessible by most types of space weapons would be shortened. Lofting or depressing could be done by sacrificing range (which in many cases may not be a real sacrifice, because the target may be at less than the maximum range), or by offloading some part of the payload (which could mean less reentry vehicles for MIRVed missiles, less explosive or less submunitions for conventional missiles). In order to give an impression of the possibilities, trajectories were computed for typical tactical ballistic missiles with 100, 500 and 1,000 km maximum range for 10% reduction in range and in payload. Table 6-2 gives the re-

Table 6-2 Parameters of depressed or lofted trajectories of tactical ballistic missiles, possible with 10% reduction in payload or with 10% reduction in range. Computations were done using the program described in the Appendix. With larger variation in payload or range, larger variations of reentry angle and flight time are possible.

Max. range with normal payload, km	100	500	1,000
max. altitude, km	39	116	230
reentry angle with optimum trajectory, degree	50	40	37
flight time, min	3.7	6.5	8.9
10% reduced payload, full range, km	100	500	1,000
lofted:			
max. altitude, km	55	180	355
reentry angle, deg.	60	50	50
flight time, min	4.3	7.8	10.8
depressed:			
max. altitude, km	32	84	157
reentry angle, deg.	38	25	26
flight time, min	3.4	5.8	7.7
Full payload, 10% reduced range, km	90	450	900
lofted:			
max. altitude, km	51	172	344
reentry angle, deg.	60	51	52
flight time, min	4.1	7.6	10.6
depressed:			
max. altitude, km	28	76	134
reentry angle, deg.	36	24	24
flight time, min	3.2	5.5	7.1

sults. As is shown here, with 10% reduction in either payload or range, elevation angles from 25 to 60 degree are possible. Thus, a radar search solid angle from 20 to 70 degree elevation will plausibly be required (this value was used in most computations).

6.1.2.3 Modifications Relating to Reentry Vehicles

Up to now, short-range missiles of one stage do not separate from the warhead after burnout, for reasons of simplicity and because there was no need to do so. In order to achieve a lower radar cross section, the warhead could be separated. The missile stage would follow on approximately the same trajectory, and could provide a false target. Alternatively, it could be exploded into small pieces.

Introduction of multiple independently targetable reentry vehicles (MIRVs) on strategic ballistic missiles was, among other reasons, in the late sixties justified by the requirement to overcome the anti-ballistic missile systems then being built. Because this increases the number of objects approaching, saturation of a defense system is easier to achieve, and the difficulties due to handling of many interceptors simultaneously increase drastically. Up to now, only intermediate-range missiles of the longest range have been equipped with MIRVs (namely, the Soviet SS-20). Comparing the payload of tactical ballistic missiles from 500 km range upward (i.e., about 1,000 kg), with the mass of a typical reentry vehicle of a strategic ballistic missile (e.g., 170 kg for an explosive yield of 100 kt TNT of the W76 warhead of the U.S. Trident I missile)[1], one sees that several nuclear warheads plus a post-boost vehicle could be carried. If conventional explosives (unitary ones or submunitions) were on top of such a missile, separation into several warheads would of course reduce the effect on each target, and the additional mass for the post-boost vehicle and several smaller thermal protective casings instead of one would have to be subtracted from the payload. Directing warheads from different missiles onto the same target (so-called cross-targeting) could to some extent make up for that reduction, but only for effects that need no terminal guidance, because it seems improbable that every conventional reentry vehicle could be equipped with an expensive and large target recognition and guidance system. Because conventionally equipped tactical ballistic missiles could only be effective against military targets if some form of terminal guidance were used (see 3.3.3 and 7.2), MIRVing (i.e. separation of warheads after the boost phase, in space, well before reentry) will not be practical here. (For submunitions see below and 6.1.2.4.)

A significant difficulty for a terminal-phase ballistic missile defense system could be posed by maneuvering reentry vehicles (MaRVs). Without a terminal guidance system, pre-programmed quasi-random course changes could be made, in the end leading to the intended target; for targets within about 10 km of the ballistic impact point, nearly the same targeting accuracy should be achievable as with a purely ballistic trajectory. If a target recognition system is present, the random changes could be updated according to the actual reentry vehicle position, and the accuracy could even be markedly increased over the ballistic case, even for larger distances from the ballistic impact point. By using such a procedure for the first time, the U.S. Pershing 2 ballistic missile is able to achieve a circular error probable of about 40 m. For reentry vehicles on a ballistic trajectory, prediction of the further course during reentry is to some extent possible (but, since the ballistic coefficient is not known, the altitude of maximum deceleration will be unknown beforehand). By producing lift the trajectory could be changed from a purely ballistic one. This would drastically increase the requirements on the computations for real-time guidance and on the interceptor maneuverability. Even if an interceptor could be guided to explode near the maneuvering reentry vehicle, and the vehicle or a terminal guidance sensor were not accidentally destroyed by a penetrating fragment, the amount of momentum conveyed by the fragments and the overpressure wave could be measured by an inertial system, and the trajectory change could be compensated for by subsequent maneuvers. Thus, maneuvering reentry vehicles would not only make guidance more difficult, but would also preclude most forms of mission kill.

A lift force is generated if the angle of attack of the reentry vehicle is changed from zero, e.g. by aerodynamic flaps. This force is roughly proportional to the drag force. The maneuvering capability would start at an altitude where the deceleration would become significant (for typical tactical ballistic missiles, at 20 to 40 km altitude, see Figs. 3-3 and 3-4), would increase to a maximum, then decrease again and persist at a lower level until impact. By using these lift accelerations perpendicular to the velocity vector, the impact point can be shifted from the ballistic one in any direction. The amount of shift possible depends in a complicated way on the characteristics of the reentry vehicle and its initial trajectory.

In order to estimate the deviations from the original impact points, trajectories of tactical ballistic missiles of several ranges were computed, where during reentry a lift force of magnitude equal to the drag force was added; in one case, the lift coefficient c_L was taken to be +1 times the drag coefficient c_D (upward, for longer range), in the other case the factor was −1 (down/backward, for shorter range). A lift-to-drag ratio of 1 is a conservative estimate (for

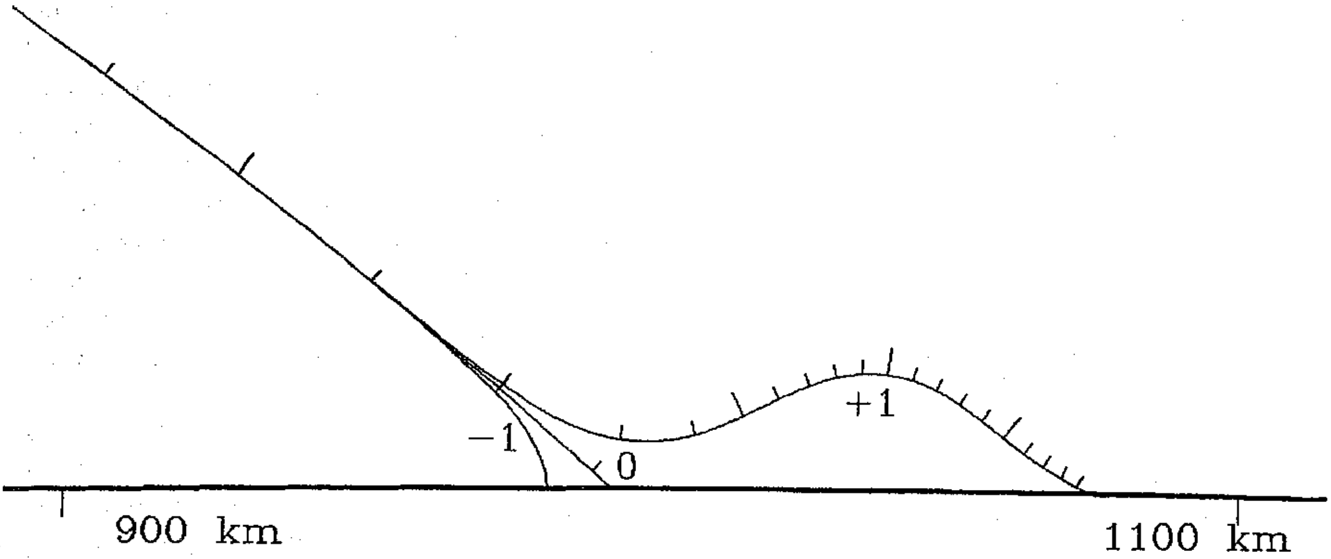

Fig. 6-1 Reentry of a ballistic missile of 1,000 km range with and without lift, computed with the program described in the Appendix. Ticks denote 10 seconds intervals after launch; the altitude 100 km is indicated. The lift force, and thus the transverse acceleration, is proportional to the air density and the instantaneous velocity; it becomes considerable at about 25 km, and has its maximum at about 8 km altitude. By appropriate control of vehicle attitude, sideward deviations are also possible.
−1: Lift coefficient equals drag coefficient, lift force points down/backwards.
0: Lift coefficient is zero.
+1: Lift coefficient equals drag coefficient, lift force points upwards.

complete ballistic missiles, 4 is a typical value of this ratio)[2]. Table 6-3 gives the results; Fig. 6-1 shows a typical example for 1,000 km range. Since the radii of curvature are large, for negative lift impact occurs in general before the trajectory could change to a backward direction. In the forward direction, on the other hand, the velocity vector can even point upwards for some time, thus the impact point deviations are much larger. (If such a skip is used, accuracy will probably decrease considerably, unless some form of guidance is added. In order to withstand the high values of transverse acceleration, mechanical strengthening of the reentry vehicle interior may be required. This should not present a serious problem, because for similar values of deceleration along the trajectory, solutions have obviously been found. For the U.S. Pershing 2, the reported "deceleration maneuver" obviously is such a skip.[3] One can speculate whether this maneuver serves the additional purpose of increasing the Pershing 2 range over the purely ballistic one.[4]) The amount of sideward movement possible by transverse aerodynamic forces can be guessed from the forward and backward figures given. In general, a maneuvering reentry vehicle could impact at any point within that region, and the defense could only know its course after having observed it. For typical ballistic coefficients, the greatest amount of drag is produced at altitudes slightly below 10 km. Deviations from the purely ballistic course by several 100 meters, which can prevent a non-nuclear interception from working, are, however, already possible at altitudes around 25 km.

Besides increasing the difficulties of defense, a gliding reentry can also be used for slowing down the vehicle to velocities at which release of submunitions without strong thermal protection becomes possible. In the gliding trajectory of Fig. 6-1, e.g., the velocity has decreased from 2.8 km/s to less than 1 km/s at the first altitude minimum. Submunitions could thus be released over the last 150 seconds of this trajectory.

The lower velocity during the gliding flight (about 0.5 km/s average in the example of Fig. 6-1) would seem to reduce the task of the defense, but this is more than compensated for by the possibility of irregular maneuvers at arbitrary times.

Table 6-3 Deviations from the ballistic range in backward and forward directions, if a lift force equal to the drag force is present during reentry, computed with the program described in the Appendix. By appropriate control of the lift, any point between these extremes can be hit. Of course, lateral deflection from the ballistic trajectory is also possible.

Range, km	backward deviation, km	forward deviation, km
100	–11	21
200	–11	28
500	–11	50
1,000	–11	80
2,000	–12	150
5,000	–15	420

6.1.2.4 Earlier Release of Submunitions

Because conventional interceptor weapons have a damaging radius of several tens of meters at most, whereas submunitions after their release may spread in the trajectory direction by several hundreds of meters, and in the perpendicular direction – depending on the intended area coverage, and on the existence of guidance systems in the submunitions – of more than 50 m, a significant effect of the defense can only be expected if the incoming warhead is hit before submunitions have been released. Earlier release is thus a possibility to enforce a higher minimum interception altitude, and thus to produce a smaller defense footprint. This is, however, limited by two effects. One is that the submunitions can probably not be equipped in a cost- and weight-efficient way with individual thermal protective shields against reentry with more than 1 to 2 km/s velocity. Still, this would allow submunitions to be dispensed at a very early time (i.e., beginning at burnout), for ballistic missiles of up to 700 km range. Reentry vehicles from larger ranges could only release their submunitions after deceleration down to such velocity had occurred, i.e. at altitudes which could range from 0 to 10 km. (The higher values hold for the lower ranges, see Figs. 3-3 and 3-4. For gliding reentry, such deceleration has occurred at altitudes between 5 and 10 km, see 6.1.2.3.) The second limiting effect applies to unguided submunitions which are to cover a certain area. Too early a release could increase the scattering circle to such an extent that the concentration of the weapons effects is smaller than required for the intended damage. For guided submunitions, however, this effect would not exist. It is, and will probably remain, difficult to assess the extent to which a potential adversary is able to keep these two effects under control. Cautious military planners will therefore opt for a minimum interception altitude against submunition-carrying tactical ballistic missiles of certainly no less than 2 kilometer, rather 5 km, and would even prefer 10 km. (Another reason for larger interception altitudes is, of course, the possibility of nuclear or chemical warheads on the missiles.) As was demonstrated in Fig. 5-9, a 5 km value would reduce the footprint extension of a Type 1 defense system against reentry vehicles with standard radar cross sections from 2,000 km range to 6 km in the forward direction, and 29 km in the backward direction. With a 10 km keepout altitude, the footprint for standard reentry vehicles from 1,000 km reduces to 9 and 53 km, respectively; interception of standard missiles of 2,000 km range is already impossible.

6.1.2.5 Decoys, Jammers, Flares

One of the biggest problems for defense against intercontinental ballistic missiles is the possibility of using a great number of light-weight decoys during the midcourse phase. Balloon-type objects in the vacuum of space would move along the same trajectories as the heavy reentry vehicles. Several measures could be taken to make discrimination more difficult, such as putting every warhead into a balloon itself, and providing the decoys with devices which would simulate the reaction of a warhead etc. Only when the so-called "threat cloud" reenters the atmosphere and arrives at about 100 km altitude, will the light decoys experience a different deceleration leading to a significant lag. This could in turn be measured by a radar to decide which targets would warrant expense of an interceptor.

Because the durations of the midcourse phase are significantly shorter for missiles of lesser ranges, it has been argued that balloon-type decoys are not a problem for anti-tactical ballistic missile defense systems. As Table 3-1 shows, however, the trajectory times at more than 100 km altitude begin to be significant at 500 km range, and are certainly so at 1,000 km and above. This means that balloon-type decoys could prevent efficient warhead discrimination, and thus prevent tracking and interceptor commit, until reentry, for ranges from 1,000 km (possibly 500 km) upward.

For smaller ranges, it is true that balloon-type decoys are reduced in value (if valued at all). For these missiles, however, new types of decoys could be developed which would match the radar cross section of a real warhead as well as its reentry characteristics, at reduced mass.[5] This could be achieved by small objects made out of a metal with a high melting point with the same ballistic coefficient as the warhead; simulating a larger radar cross section could be done by appropriately shaping the nose. With some engineering, it may also be possible to produce a similar infrared signature. Such a decoy could have a mass of 1 to 5 kg; with typical payloads of shorter-range ballistic missiles of 500 to 1,000 kg, it should be possible to carry 10 to 20 decoys without significant reduction in warhead size. For shorter-range missiles, the payload/launch mass ratio is markedly above that of longer-range missiles (i.e., about 0.5 vs. less than 0.1, see Fig. 3-1); therefore, on a launch mass basis addition of these heavier decoys would be relatively less expensive. The effect would be that discrimination would be very difficult, if not impossible, possibly until impact, or at least until warheads and decoys had arrived at an altitude where deceleration increases markedly, and different sizes of the reentry wakes could be sensed by radar. It is difficult to estimate this altitude, but values between 20 and 50 km seem to be a conservative estimate (i.e., favoring the defense). This would enforce an effective detection altitude of that magnitude, which is even below that of balloon-type decoys.

The resulting changes of the defense footprint area have been computed for a Type 1 interception system and are shown in Table 6-4. Here, radar detection has been required in addition (different from Fig. 5-10). With 50 km, the footprint area is most affected in backward directions. With 20 km effective detection altitude, marked reductions also in the forward

Table 6-4 Margins R_{FF} and R_{FB} of the footprint areas in the forward and backward directions, of a Type 1 defense system, against reentry vehicles from several ranges, for different effective detection altitudes h_{Det}. The minimum interception altitude is $h_{min} = 2$ km. Radar detection is assumed necessary, i.e. effective detection occurs only if the objects are simultaneously within the radar detection range, and below the effective detection altitude (this differs from Fig. 5-10). The radar cross section is $\sigma = 0.01\ m^2$, the value of current long-range reentry vehicles.

	Effective detection altitude					
	100 km		50 km		20 km	
Range km	R_{FB} km	R_{FF} km	R_{FB} km	R_{FF} km	R_{FB} km	R_{FF} km
100	149	80	149	80	29	28
200	251	54	54	44	24	22
500	115	30	45	30	15	11
1,000	54	21	31	21	7	2
2,000	29	13	22	13	–	–
5,000	12	2	12	2	–	–

direction are seen; here, missiles from 2,000 km range and above can no more be reached at all.

If the ballistic missiles were accompanied by jamming transmitters, the search radar could be blinded; if the radar utilized adaptive side-lobe nulling, jamming would at least work in the general direction of the transmitter.[6] Because the received power scales with the inverse distance squared, and the transmitters would only be switched on when they reach the search detection distance, kilogram-sized escort jammers will suffice to deny radar detection of the reentry vehicles. (For the special type of radar blinding possible by nuclear explosions, see 6.1.2.7.)

Infrared detection systems could be fooled by additional sources of infrared radiation. Presently, infrared-emitting flares are routinely used to confuse infrared seekers of anti-air missiles. One new kind of source could be created by artificial high-altitude clouds which strongly scatter long-wave infrared radiation.[7] Future air- or space-borne search and detection systems will become more sophisticated against tactical ballistic missiles. However, it is improbable that a reliable detection and discrimination of warheads over hundreds of kilometers, or even more than 1,000 km, could be possible in the presence of a "firework" of many different infrared sources.

6.1.2.6 Changes Concerning the Boost Phase

Detection of the missile exhaust flame could possibly be made more difficult by a smoke curtain. Irregular acceleration could – at some expense in the overall efficiency of the rocket motor – impede the targeting of beam weapons. A very effective countermeasure against possible future beam weapons would be to shorten the boost phase of the tactical ballistic missiles. This would come at a moderate expense in burnout velocity, payload, or range. Easier than with intercontinental ballistic missiles, intermediate-range missiles could be designed to burn out at less than 80 km altitude, and thus could not be attacked during the boost phase by x-ray laser or particle beam weapons. Tactical missiles could achieve burnout at about 40 km, and short-range missiles at about 20 km. Thus, the time span for a possible laser weapon intercept (between penetrating a cloud cover at maybe 10 km, and burnout) would be 10 to 30 seconds, which makes interception highly improbable. For space-based kinetic energy weapons, the short boost phases of today's missiles already prevent any chance of interception before burnout.

6.1.2.7 Salvage Fusing of Nuclear Warheads

Most kinds of non-nuclear interception techniques (and also some nuclear explosion effects) rely on some kind of external manipulation of the warhead, such as: slow heating by laser irradiation, explosive ablation by high-power light or x-ray pulses, mechanical shock from an overpressure wave, hits by fragments or massive objects. In any of these cases, the thermal or mechanical effect needs some time to penetrate the bomb material and damage its interior mechanism. By salvage fusing, a bomb engineer can try to trigger the explosion on any kind of sensed external manipulation. Such a mechanism would be activated after the missile has traveled some minimum distance from its launch point. This in general would not effect damage at the intended warhead target; because of the fireball produced and its associated side effects, however, radar or infrared sensors of defensive systems could not penetrate a region of 1 to 2 km diameter for tens of seconds.[8] Additional warheads following with some delay could then pass through the same region unhindered by the defense, possibly penetrating to the target. (For very hard and heavily defended targets, this technique might have to be applied several times consecutively – this "laddering down" would significantly raise the "attack price".[9] For anti-tactical ballistic missile defenses in Europe, such heavy defenses are unlikely; the least salvage fusing would achieve is severely disturbing the defensive system, as well as space-, air-, and ground-based surveillance in general.)

In order to estimate whether or not salvage fusing is possible for the different external interception mechanisms, one has to ask if the velocity with which the damage effect travels into the warhead suffices to reach the imploding chemical explosive or the fission trigger, before a critical mass has been formed. Sensors immediately below the thermal protective layer could detect and relay the external effect within less than one microsecond. Relaying this signal to electronic controls, deciding that their magnitude warrants salvage fusing, and igniting the chemical explosive lenses could be done within several hundred nanoseconds. A typical detonation front velocity is 8 to 10 km/s;[10] with an explosive thickness of roughly 0.1 m, this translates to 10 μs until compression of the fission trigger material (plutonium-239 or uranium-235) starts. Typical compression times are less than one microsecond for advanced nuclear weapons states, up to 10 μs for less modern implosion weapon types.[11] After the critical mass has been formed, buildup of the chain reaction until its total energy is released takes about 0.5 μs. (A consecutive fusion stage would take not much longer.) Unless the external effect would disrupt the critical assembly in this very 0.5 μs, release of several kilotons TNT energy eqvivalent from the fission trigger could no more be prevented. (Only if the external effect would reach the fusion assembly a short time afterwards, there is a chance that the full fusion energy release will not be achieved.) The question: is salvage fusing possible? then boils down to the question: can the external effect arrive at the fission material before the detonation wave (or at least within 0.5 μs after it)?

For an external thermal effect with its low propagation velocity, there is no question that the explosion could be triggered in time. For explosive ablation or impact of fragments which are stopped in the upper layers, the mechanical shock produced propagates with the velocity of sound into the warhead material, for compact solids on the order of 5 km/s. If the impact is at the front of the warhead (see Fig. 6-2 a)), a time delay of about 50 μs is needed for the shock wave to travel through the inert warhead nose to the explosive (about 0.25 m). Within this time, compression is well feasible. For nearly orthogonal impact at the cone mantle (Fig. 6-2 b)), the external protective layer introduces a delay of about 0.02 m / 5 km/s = 4 μs. If a sensor could be placed in front of a layer providing additional 2 μs delay, the chemical explosive on the side hit could be triggered before the shock wave arrived. Afterwards, the shock wave would propagate in the high pressure gas of the burnt explosive with less than a few km/s, trailing behind the explosive detonation front which moves with about 10 km/s – this means that even in this case compression of the fission trigger would be achieved before the shock wave arrived.

The conclusion is that for any kind of external manipulation which does not travel faster than the velocity of sound into the warhead material, salvage fusing should work reliably with only minor changes in the warhead design (addition of sensors over its periphery, and changes in the trigger electronics).

Sufficiently fast propagating internal damage could be possible, if a massive object would hit the warhead with a relative velocity so high that its parts – after the initial deceleration in the warhead – still move with a velocity markedly above 10 km/s. A conservative lower limit for this would be a relative velocity of 20 km/s before impact. For warheads of tactical ballistic missiles with 3 to 6 km/s and opposite velocity vectors (head-on impact), this would necessitate interceptor velocities of 15 km/s and more – this is not possible at a reasonable cost using chemical rockets, and may only be achievable using electromagnetic acceleration. Therefore it will not be at hand for about the next 15 years. Because of the 10 μs delay introduced if the warhead would be hit at its nose, a further requirement would be either opposite

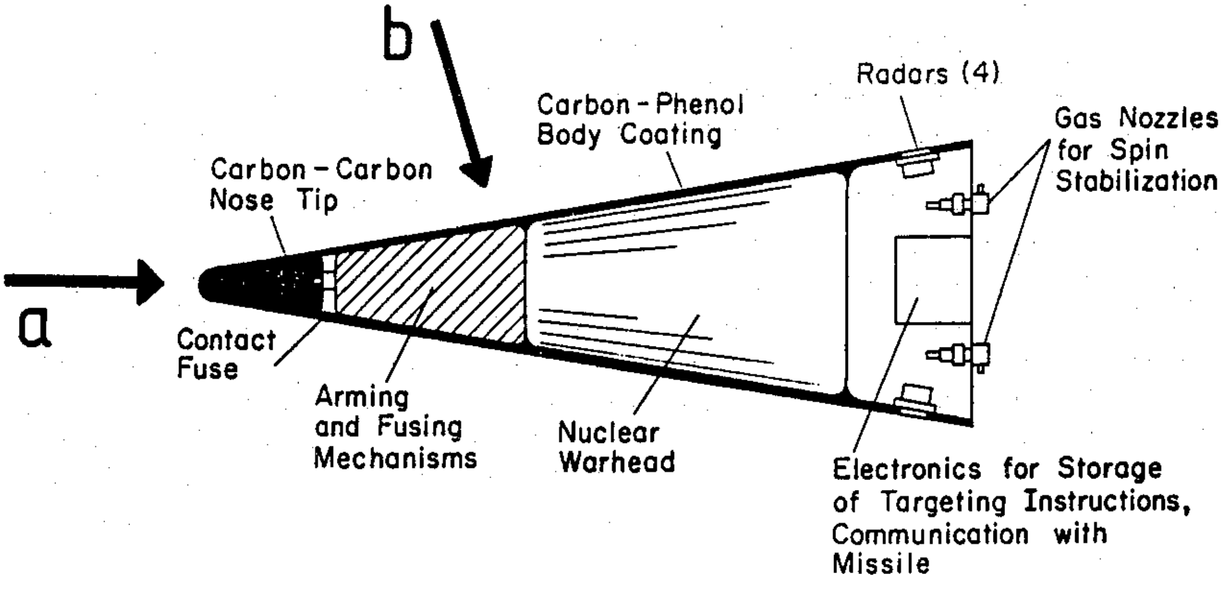

Fig. 6-2 Schematic drawing of a reentry vehicle of an ICBM.[12] Typical dimensions are: length, 1.5 m; base diameter, 0.6 m; nose radius, 0.04 m. Two types of collision with fast objects are indicated.

impact at the cone mantle, which would drastically increase the targeting requirements. An alternative would be impact on the cone mantle from a sideward direction (see Fig. 6-2 b)). In this case the reentry velocity is roughly orthogonal to the interceptor velocity so the latter would have to be above 20 km/s. Thus, the statement arrived at in the case of the shock wave propagation need not be modified for the next decade or more. Should interceptors with 15 or 20 km/s be deployed at a later time, introduction of a proximity sensing device with a somewhat larger redesign of the warhead could be an effective counter. Proximity fuses, e.g. working with millimeter-wave radar, are used routinely with air defense munition.[13] Even if an object approaching at 20 km/s were sensed only at 1 m distance, this would provide for 50 μs time – more than enough for safely triggering the nuclear explosion. It may be that the plasma sheath during reentry could not be penetrated by radar, but this principle would at least reliably work in space.

In conclusion, salvage fusing will be possible for the foreseeable future for any kind of external interception. Only nuclear radiation (from nuclear explosions or from particle beam weapons) penetrating at (nearly) the velocity of light could provide a chance to prevent salvage fusing.

6.1.2.8 Using New Defense Technologies for the Offense

Many of the new weapons technologies that are being developed for defense against (longer- or shorter-range) ballistic missiles provide significant offensive capabilities of their own. Whereas some destruction mechanisms could only work in space, others could at least in principle also be used for strikes into the atmosphere, or from within the atmosphere. This holds e.g. for laser weapons.[14] For space-based kinetic kill vehicles, it is at least conceivable that they could be modified and used for precision attacks (conventional or nuclear) against ground targets.[15] Insofar as one would expect some symmetry in capabilities between the sides, it may well be that the fear of non-nuclear surprise attacks against high priority military targets in Western Europe will rise markedly with introduction of new kinds of space-based weaponry, which was originally motivated by the fear of surprise attack with conventional ballistic missiles (see 2.2 and 7.2).

Several of these possibilities have been mentioned already in the SDI debate. A new possibility is the idea of accelerating tactical projectiles by electromagnetic launchers. It is not at all clear if this technology will at some time allow shooting objects of several 100 grams against flying targets. There has, however, even been promoted the idea to launch space payloads using this technology.[16] The U.S. SDI Organization already envisages utilizing such hypervelocity gun technologies for anti-armor, anti-aircraft, and fleet defense operations.[17] If heavy investment in electromagnetic acceleration bears fruit, it could happen that payloads of 10 to 50 kg could eventually be launched also, with muzzle velocities of several kilometers per second. This would allow ballistic ranges of more than 1,000 km. If such launchers could be made mobile, and salvos could be directed at several different targets, and the reentry and guidance problems could additionally be solved, then similar fears of conventional surprise attack could arise even without any tactical ballistic missile. Of course, all these conditions are difficult to fulfill, and may even turn out to be impossible. They should not, however, be dismissed lightly.

6.1.3 Offensive Countermeasures

If anti-tactical ballistic missile defenses are to be attacked directly, the main problem is to know their locations. Whereas interceptor launchers may be difficult to locate and target in real time, the radar energy transmitted in the search mode could be used for that purpose. Even though radar silence could be ordered for most search radars, some of them are bound to transmit at some time, if the defense is intended to work. These radars betray their position quite effectively. Missiles seeking radar emitters could be used to hit the radars and destroy them with relatively little conventional explosive. In this way, for one radar destroyed, a whole battery of interceptor missiles could be rendered inoperable. The USA has available for such purposes the "High-Speed Anti-Radiation Missile HARM", which approaches with supersonic velocity.[18] The West-German companies Dornier and Messerschmidt-Bölkow-Blohm are developing a "Klein-Drohne Anti-Radar KDAR" (small anti-radar drone), which travels at only 200 km/h (i.e., 0.16 times the velocity of sound), and is intended to search and destroy radars of air defense systems at up to 100 km distance.[19] Of course, similar missiles or drones are, or will be, available to the other side.

High-flying aircraft with infrared sensors will be highly visible on radar systems of the other side. Because of their light-weight construction, they will not be able to out-maneuver anti-air missiles directed against them. Having considerable detection range, they could fly more than 100 km off the border, out of range for most existing anti-aircraft missiles. (Of the current Soviet air defense missiles, only the nuclear/conventional SA-5 with 300 km range could be used at such distance.[20] On the NATO side, only the now outdated dual capable Nike-Hercules with 140 km range was capable of comparably deep anti-aircraft attacks.[21]) Future air defense systems of longer range should be able to attack these aircraft at their operating distance, maybe in interaction with components of anti-tactical ballistic missile systems. In this context, one should notice that in a U.S. Senate Committee discussion on the funding of the Advanced Air-to-Air Missile and the Advanced Surface-to-Air Missile, it was noted that the "Outer Air Battle Study" of the U.S. Navy "confirmed the need for air-launched and surface-launched missiles of very long ranges to provide an offensive antiair warfare capability against enemy bombers, such as the Backfire, before they reach their weapons release points".[22] In a scenario of global space weapons, attack against an infrared-sensor carrying aircraft with laser weapons should present a markedly easier task than interception of the much faster and smaller tactical ballistic missiles. Guidance for space-based kinetic energy weapons for attacks at moving targets in 15 to 20 km altitude will present a problem; together with space-based radar and infrared observing stations, and an appropriate communications systems, this possibility can at least not be excluded.

If both sides command a global weapons system in space for intercepting ballistic missiles of all ranges, of course these weapons could attack each other, too (and they would probably spend 90% of their time watching the other system for a possible attack). Since this has to do with a qualitatively new kind of strategic antagonism, it will not be treated in this report.[23] It is at least prudent to assume that, if a conflict had started, neither side would remain in continuous possession of its space weapons, and thus of its missile defense capacity.

6.1.4 Counter-Countermeasures

Against several of the countermeasures mentioned, counter-countermeasures could be taken. One kind would enhance the capability of the defense systems (e.g. increase the radar power and antenna area, augment the interceptor velocity, maneuvering capability, and range; include interception of aerodynamic targets). Another would raise the numbers of defense systems together with those of the ballistic missiles or of their reentry vehicles. Radiation-searching missiles could be impeded by silence of all but a few radars in a netted system, or by electronic countermeasures like false radar transmitters at different locations. As mentioned, the main counter-countermeasure against salvage-fusing of nuclear warheads is using a nuclear interceptor. As usual, a contest of measures, countermeasures, counter-countermeasures etc. is to be expected. The next section tries to give an answer to the question, whether this contest would favour the offense or the defense for the foreseeable future.

6.2 Expected Efficiency of Anti-Tactical Ballistic Missile Systems

6.2.1 General Comparison of Defense Against Aircraft, Tactical, and Strategic Ballistic Missiles

Arguments brought forward in favour of anti-tactical ballistic missile systems often include comparisons with anti-aircraft defense on the one hand, and defense against strategic ballistic missiles on the other hand. Whereas some SDI proponents give the impression that interception of long-range ballistic missiles is easy, and that the same would of course apply to missiles of shorter ranges, most proponents of defense against tactical ballistic missiles tend to acknowledge the difficulties with long-range missiles, and state that defense against shorter range missiles is qualitatively easier because of their reduced velocity, and less amount of flight time spent in space. If the notion of "extended air defense" is used, this normally comprises the idea that tactical ballistic missiles can be intercepted similarly to aircraft by some incremental change of air defense systems. The following paragraphs will make some general observations on the relative difficulties of intercepting aircraft, as well as tactical, and strategic ballistic missiles.

Concerning aircraft, their radar cross sections are at least a hundred times above those of reentry vehicles of tactical ballistic missiles, and their velocities are 3 to 10 times lower. Because their flight altitude is limited to less than 20 km, the solid angle to be searched will also be lower by perhaps a factor of 3. Together, this makes for a radar detection range at least ten times higher. Thus, much more time is available for interception, and the defense footprints are correspondingly greater. (To make use of this possibility against low-flying aircraft, an elevated radar platform will be required.) Even in the case of stealth aircraft (with a radar cross section on the order of 0.01 m^2,[24] i.e. roughly comparable to that of a ballistic missile), the other two factors provide for a greater detection range. In addition, interceptors can be faster than the aircraft, so a tail chase after overflight of the defense position is possible; the same holds at least in principle for changing the course and following, should a first head-on approach have failed. The area which could be hit by fragments is 20 to 100 times larger for aircraft than for reentry vehicles. For an aircraft, continuing its path depends on the steady functioning of wings, control flaps, and the engine; on the other hand, a reentry vehicle is an inert object falling towards its impact point. Throwing it from its further trajectory requires relatively more damaging effect. Thus, the conclusion is that there is a distinct qualitative step between anti-air and anti-tactical ballistic missile defense. It may be possible to provide upgraded air defense systems with some capability against a single, present-day, short-range missile (having a ceiling of 40 km, approaching with 0.6-0.8 km/s, and presenting a relatively large radar cross section because the warhead is not separated from the missile). For a significant capability against ballistic missiles of ranges above 100 km, new interceptors (with higher velocity, course control by thrusters, and new interception warheads) will be required, and search will necessitate inclusion of airborne, and even space-borne, sensors. All this tends more to resemble defense systems against strategic ballistic missiles than anti-aircraft systems.

Concerning the relative difficulty of intercepting tactical, as opposed to strategic, ballistic missiles, one has to note several counteracting tendencies. Whereas the velocities of the former are indeed lower, the total flight time is also less. In addition, nose tips of tactical reentry vehicles can be sharper, and radar cross sections smaller. Because tactical ballistic missiles arrive at larger elevation angles, the flight times through the atmosphere, i.e. the time after discrimination of balloon-type decoys becomes possible, is roughly comparable for missiles of long, as well as of intermediate ranges. Radar search solid angles have to cover much larger elevation and azimuth ranges than with intercontinental ballistic missiles (in this respect, defense against tactical ballistic missiles is comparable to defense against sea-launched ballistic missiles launched from submarines in forward positions). Numbers of warheads are of the same order of magnitude, and reloading is easier with tactical missiles. All these tendencies taken together give the impression that anti-tactical ballistic missile defense in general will not be easier than defense against strategic ballistic missiles (with the possible exception of short ranges, i.e. up to perhaps 200 km).

In conclusion, there is much more similarity between anti-tactical ballistic missile defense and defense against strategic ballistic missiles, than there is between the former and anti-air defense.

6.2.2 Defense Efficiency Against Nuclear Tactical Ballistic Missiles

6.2.2.1 Defense of Military Targets

Here, a comparison with the defense of ICBM silos is instructive. Today, ICBM silos are constructed to withstand overpressures of 14 Megapascal (2,000 psi) or more.[25] This means that a nuclear explosion of 100 kt TNT yield (typical of a tactical ballistic missile warhead, strategic ones are more than threefold higher), would fail to damage the silo if it occurs at more than 170 m distance (see Fig. 3-7). So, for defense of silos against ICBM warheads, the keep-out range which must be enforced by a defense will be 300 to 500 m. Nevertheless, taking into account the possible countermeasures on the one hand, and preferential defense tactics on the other hand, there is agreement in the U.S. defense community that the so-called attack price of terminal-phase defense of a silo could be increased by great effort to anything between two and eight warheads (i.e., if an attacker would expend that many warheads for precursor attacks or even for complicated "ladder-down" tactics, the probability of silo survival would be sufficiently low, say below 10%).[26] This is only achieved at the expense of sacrificing some silos by leaving them totally undefended. In any case, explosions of nuclear weapons in the vicinity of some silos could not be totally prevented. Due to the destructiveness of nuclear weapons, such sacrifices would not significantly reduce the second-strike capability of a defending side. (The so-called "collateral damages" on the population would nevertheless be catastrophic.[27])

The situation with military targets in Europe is markedly different. Whereas normal buildings, radars, or parked aircraft will be damaged with overpressures of 35 kilopascal (5 psi) or less, the hardest objects are concrete-reinforced bunkers, which are damaged with overpressures of 280 kPa (40 psi) (with the possible exception of a few central strategic command posts). Damage by a 100 kt TNT warhead would reach out to 2 kilometer against normal installations, and to 700 meter against hardened bunkers (see Fig. 3-7). Therefore, a successful defense of a military target would require keeping any nuclear explosion at such an increased distance. In addition, military targets in Europe are on the average more than 20 km apart, so that one defense system could cover only one target, and the cost advantages of preferential defense could not be utilized. Because great accuracy is not required with such high damage radii, damaging effects of a first explosion on a following one (so-called "fratricide") can be avoided, and trajectory changes do not matter. Therefore, no "laddering down" using several warheads will be necessary; the attack price is likely to increase, from one in the undefended case, to no more than two warheads with a defense. (Which number, taking into account the limited reliability of missile and warhead, may have already been planned for in the undefended case.) Lastly, loss of some portion of military installations in Europe counts relatively more heavily than loss of the same portion of ICBM silos. For all of these reasons, protection of military targets in Europe from nuclear ballistic missiles by ground-launched interceptors is no practical possibility. (With respect to the collateral damage to the civilian population, the prospects are roughly similar to those for an attack on ICBM silos.[28])

Adding space-based sensors would not change this statement, as long as the decoy discrimination problem remains unsolved. As stated above, many actions could be taken to retain this state of affairs. Introduction of an overlay of space-based weapons would not change the picture either; one reason is the discrimination problem, another one is the possibility of attacks in space.

6.2.2.2 Defense of Population Centers?

Efficient defense against nuclear attacks on cities would require an almost impenetrable defense system. The possibility of this happening is very remote, and will in all probability remain so, because the respective other side can react to defense buildup in many different ways. This conclusion holds for strategic ballistic missiles;[29] in the case of Europe, the spectrum of nuclear-weapon carriers is even larger. That there is not a perspective for population protection is underscored by the fact that even proponents of an SDI-like "European Defense Initiative" avoid to make such a promise, and prefer to talk in a more vague manner about "a change from the current strategy of Mutual Assured Destruction ... to a strategy of Dissuasion, strengthening Deterrence, based on the denial of assured destruction."[30]

6.2.3 Defense Efficiency Against Conventional Tactical Ballistic Missiles

For conventionally equipped tactical ballistic missiles the keep-out distance could be lower, and salvage fusing would not make sense. In order to assess the possible efficiency of defense systems against those missiles, therefore, one has to take a deeper look at the potential countermeasures and counter-countermeasures, than was necessary in the case of nuclear warheads. The answer will be more dependent on the details of the respective implementations. First, these details, however, are not known in advance. Second, both sides will try to keep plans and projections secret. The following arguments therefore try to make an educated guess only. As will be argued at the end of this section, the accuracy of this guess is not too relevant.

Of the several countermeasures mentioned in 6.1, it seems probable that increase in missile numbers, MIRVing, reduced radar cross sections, classical and new types of decoys will for the next 10 to 15 years be able to dominate over the respective counter-countermeasures. This means that discrimination of warheads from decoys could only take place after reentry (altitudes from 100 down to 20 km or even less), the footprint areas would be correspondingly small (down to zero), and saturation by high numbers of warheads will be able to overwhelm defense systems. Sending anti-radiation missiles would either exhaust the interceptors available for each radar, or force most radars to shut down, thus opening the way for a significant portion of tactical ballistic missiles launched simultaneously.

Airborne infrared detection systems which could be deployed after 1995, would probably become vulnerable to longer-range anti-air or anti-tactical defense missiles at about the same time. There is not much chance for them to be able to discriminate the warheads from the decoys for the next 15 years.

In a more distant future, space weapons could come into play. But because these would work on both sides, prospects for one side achieving most of its goals in a conflict (i.e., destroying the space weapons of the other side while keeping the own ones intact, and at the same time effectively attacking ballistic missiles), are rather dim.

Another hint on the projected defense efficiency may come from the comparison with air defense systems. As outlined above, this task is markedly less demanding. Nevertheless, historical experience shows that seldom have the loss rates of aircraft been above a few percent per sortie, despite massive anti-aircraft gun and missile use. In World War II, the overall attrition rate caused by air defense forces was 0.9%; in the Vietnam war, the figure was 0.3%; in the 1973 Arab-Israeli war, the Israeli Air Force loss rate averaged 0.8%.[31] For single air raid campaigns, attrition rates of 2 – 6% per sortie for World War II, 2% per sortie for the Vietnam war, and 2% per sortie for the Arab-Israeli war have been reported.[32] This is militarily significant, however, since aircraft are planned for multiple use, and losses accumulate with the number of sorties. It is reported that the U.S. Air Force recommends breaking off operations if the attrition rate reaches 2% per sortie (because of the loss of experienced crews)[33]. Also interesting is the number of anti-air missiles required per downed aircraft: in order to shoot down a low-flying aircraft, 3 to 6 modern missiles will have to be expended.[34]

The conclusion is that it may be possible to achieve some degree of defense effectiveness against limited attacks of conventional tactical ballistic missiles at a few very important points, using very high expenses. In the light of the possible countermeasures, and of the experiences with anti-air defense, for the foreseeable future it seems improbable that defense efficiencies against massive attacks could increase above a few percent. Because ballistic missiles are expendable weapons without a crew, loss rates like this do not matter from a military point of view. Rather, they could be compensated for in advance by increased production and deployment.

These low expectations of defense effectiveness do not have much relevance, though, insofar as even without any defense, conventional ballistic missiles do not pose a serious threat against most military targets in Europe.[35] This holds for the generation of Soviet missiles being introduced at present because of insufficient accuracy. It would also hold for a hypothetical conventional Pershing 2 or other Western conventional ballistic missiles, which might have come near the accuracy required, but only against fixed extended targets (i.e., airbase runways; here, however, rapid repair measures could prove more effective than missile defense). Real-time reconnaissance of mobile objects deep inside the other side's territory will remain difficult and subject to countermeasures. Fixed point targets (like bunkers) could efficiently be protected by subdivision and addition of concrete or soil. Rather high increases in tactical ballistic missile numbers would be required to achieve success in a conventional attack; other, aerodynamic, missiles will generally be more appropriate for the intended damage. Therefore, low levels of projected defense effectiveness will not much reduce the already low level of damage effects expected by the use of conventional tactical ballistic missiles.

6.3 Some Arguments Concerning Cost Effectiveness

Cost-effectiveness of a ballistic missile defense system could be measured by several figures of merit. Cost-effectiveness at the margin is given if, at some state of respective investment, adding one offensive unit is more expensive than adding the amount of defense needed to compensate for this. Another measure would compare the cost of the defense with the cost of the protected installation. A third measure would include the total accumulated costs of defense and offense up to the time in question. The technical perspective of the present study and the early stage of development of many weapons and countermeasures only allows some conclusions on the first measure.[36]

Concerning the marginal cost-effectiveness, some tendency can be seen by looking at the costs of present ballistic missiles, and at the actual or projected costs of interceptor missiles. The U.S. Lance, a nuclear short-range (110 km) missile introduced in 1972 and produced until 1980, cost about $ 200,000 per copy (system costs were about $ 500,000).[37] The average cost of the Pershing 1A (nuclear, 720 km range), produced until 1981, was $ 2 million; the Pershing 2 (nuclear, 1,800 km range) costs about $ 5 million. For a conventional version (including terminal guidance) $ 2 million has been mentioned.[38] On the other hand, a modern Patriot air defense missile costs about $ 650,000; with the proportionate share of the radar and other infrastructure, this figure increases to about $ 1.7 million.[39] A new smaller interceptor like that used in the FLAGE experiment will be lower, but costs of an extended range follow-up like the ERINT would increase again. Without giving too much weight to the subtleties, one gets the impression that a modern interceptor missile is in the same cost class as a ballistic missile of about 1,000 km range. Taken one per one, cost-effectiveness at the margin could exist here. Considering the air defense experience, however, one would conclude that the ratio of defense to offense costs would worsen as more interceptors would have to be committed against one incoming missile (of course, an offense-conservative calculation would have to include the additional ballistic missiles deemed necessary to overwhelm the defense). Against short-range missiles, even on a one per one basis the defense seems to be at a disadvantage.

The picture shifts even further against the defense, if attacks against the radar using anti-radiation missiles are included. One of the anti-radar drones mentioned above is projected with a system cost of about $ 170,000;[40] a U.S. HARM is listed with about $ 280,000.[41] Taking the Patriot system as an example, where one radar is used for every 20 to 32 interceptor missiles, between 120 and 320 anti-radiation missiles could in theory be expended per radar, before the cost ratio would turn in favor of the defense. (Incidentally, the number of trajectories that the Patriot battle management system can handle, is 100.[42]) High numbers of anti-radiation drones per radar are not totally fantastic; for the West-German Air Force, a total figure of several 1,000 anti-radar drones has been mentioned.[43] For a realistic assessment, effects and costs of countermeasures like decoys and jamming transmitters would have to be included. This would be very difficult even if detailed information were available. The general impression is, however, that decoys and jammers could be produced with substantially less mass than a reentry vehicle, and that thus the cost for their production and transport to altitude would lie correspondingly lower. This would further shift the marginal cost-exchange ratio in favour of the attacker.

Concerning possible space weapons of the future, statements about cost-effectiveness are difficult to make because architectures of the respective weapons systems have not yet been defined. A general remark seems justified, however: one should not compare future space weapons with present ballistic missiles. Rather, cost ratios between different kinds of space attack and defense weapons have to be looked at. It seems doubtful that cost-effectiveness considerations would drive a bi- or multilateral space arms race to passive and defensive postures; because of the inherent vulnerabilities and the extreme short warning and reaction times involved, the opposite has to be feared.[44]

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34 Borgart (note 31).

35 The following arguments are expanded in: B. Morel, T. Postol, Non-Nuclear Soviet Tactical Ballistic Missiles: A Threat to NATO?, Part B, in: J. Altmann, B. Morel, T. Postol, T. Risse-Kappen, Anti-Tactical Missile Defenses and West European Security, HSFK-Report 4/1987, Frankfurt/M.: Peace Research Institute Frankfurt, October 1987; and: B. Morel, T. Postol, A Technical Assessment of the Soviet TBM Threat to NATO, in: Hafner/Roper (note 5). A more detailed presentation will be given in the forthcoming report by B. Morel and T. Postol from the Center for International Security and Arms Control, Stanford University, Stanford CA. See also: D. Rubenson, J. Bonomo, The role of ATBM in NATO strategy, Survival, vol. XXIX, no. 6, pp. 511-527, November/December 1987; D. Rubenson, J. Bonomo, NATO's Anti-Tactical Ballistic Missile Requirements and Their Relationship to the Strategic Defense Initiative, Report R-3533-AF, Santa Monica CA: RAND Corporation, December 1987.

36 For some arguments on the total costs of anti-tactical ballistic missile defenses see: 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, pp. 135-136.

37 For the following data on missiles and prices, see: Cochran et al. (note 1); Military Cost Handbook 1986, Seventh Edition, Fountain Valley CA: Data Search Associates, 1986.

38 D. R. Cotter, Potential Future Roles for Conventional and Nuclear Forces in Defense of Western Europe, pp. 209-253 (here: p. 240), in: Strengthening Conventional Deterrence in Europe – Proposals for the 1980s, Report of the European Security Study ESECS, London: MacMillan, 1983.

39 Department of Defense Appropriations for 1983, Subcommittee of the Committee on Appropriations, U.S. House of Representatives, Ninety-Seventh Congress, Second Session, Part 1, p. 635 (quoted after: van Gool et al. (note 36), p. 136).

40 Heckmann (note 19).

41 Military Cost Handbook (note 37).

42 Expensive, but necessary: the PATRIOT surface-to-air missile system, Military Technology, no. 10, pp. 33-50, October 1984.

43 Heckmann (note 19).

44 See e.g.: Altmann (note 23), Ruquist (note 23).

7. Anti-Tactical Ballistic Missile Defenses and Strategic Stability

Following a short definition of strategic stability (7.1), 7.2 discusses the effectiveness of conventional tactical ballistic missiles; offensive strikes at missile launchers are covered in 7.3. Several properties of projected anti-tactical ballistic missile defense systems which may have a bearing on strategic stability are the subject of 7.4. On this basis, consequences for arms race stability are discussed in 7.5. Crisis stability is dealt with in 7.6.

7.1 Definitions of Strategic Stability

In the present study the notion of *strategic stability* is used in its classical narrow meaning, i.e. as a measure of security against outbreak of war, and a measure of absence of pressures for arms buildup.[1] Strategic stability against a first attack exists, if the damage which an attacker has to expect as a consequence, is unacceptably high. Specifically, one speaks of *crisis stability*, if, in a crisis, no side could, by preemptive attack on weapons systems of the adversary, reduce its damage in such a way that this seems a more favorable alternative than continuing to wait. *Arms race stability* could be looked at as the long-term aspect of strategic stability. It exists, if the weapons systems of one side do not exert pressures on the other to increase the numbers or to introduce new kinds of weapons. (Other, e.g. internal, motives for quantitative or qualitative arms buildup are neglected in this view.)

Strategic stability must not be confused with strategic parity. Whereas rough parity can contribute to strategic stability, it is by no means sufficient. A totally symmetric situation can be highly unstable, e.g. if both sides have weapons which can destroy a great number of weapons of the other side, are vulnerable, and have short reaction times.

Of course, stability in the relations between states comprises more than strategic stability. Political, economical, psychological aspects can contribute significantly to the prevention of war. Under certain circumstances, the strongly military-oriented considerations on strategic stability totally lose their relevance, namely if the relations between states are such that no attack is feared in the first place (cf. USA – Canada, France – West Germany). When mutual attack fears exist, arms control and arms reduction agreements may directly improve crisis and arms race stability; in a more general sense, they can also contribute to better over-all relations.

7.2 Is the Fear of a "First Strike Using Conventional Tactical Ballistic Missiles" Justified?

If fears of a surprise attack against NATO military installations by WTO tactical ballistic missiles with conventional warheads, which would have consequences up to a "strategic disarming strike",[2] were justified, this would certainly be a destabilizing development; if, second, defense systems against such ballistic missiles would prove effective, and if they, third, had no destabilizing effects of their own, deployment of such anti-tactical ballistic missile defense systems would indeed increase crisis stability. These are three preconditions, however, and all of them are not likely to be fulfilled. One precondition is the expected efficiency of defense systems, which, as discussed in 6.2, will probably not exceed a few percent. Another precondition, the question of destabilization by the defenses themselves, will be treated in the rest of this chapter.

The main assumption on which this fear rests, is the alleged ability of the WTO to efficiently destroy important parts of NATO military infrastructure using conventional ballistic missiles. A profound analysis of this proposition was done at the Center for International Security and Arms Control of the Stanford University, the results of which shall be summarized here:[3]

- Ballistic missiles have much less load capacity than aircraft, and can be employed only once. Several missiles would be necessary to transport the amount of munition which a fighter plane could carry in a single mission.
- If mobile targets (like air-defense radars) are operated reasonably well, they could not be targeted efficiently by ballistic missiles, because of uncertainty in their location, which is added to the targeting error of the missile system itself. Already existing (and planned) airplanes, stand-off and cruise missiles as well as radiation-seeking projectiles do (and will) provide more efficient capabilities for attacks against mobile targets than ballistic missiles.
- Due to the limited amount of conventional explosives which can be carried by a tactical ballistic missile, suitably hardened and subdivided protective bunkers could not be significantly damaged, either by a unitary warhead or by submunitions.
- Finally, attacks against air bases would require targeting accuracies of around 30 m, which need some form of terminal guidance (as used in the U.S. Pershing 2 missile), and will not be generally used on WTO ballistic missiles for several years to come. Modern military aircraft can take off and land at strips of 300 to 500 m length; moreover, airbases have alternate taxiways available. In order to render an airbase inoperable, each runway and each taxiway would have to be cut completely at several positions. Even if targeting errors were negligible, attacking one airbase would require around 10 conventional ballistic missiles, and such attacks would have to be repeated every 4 to 6 hours due to the already existing fast repair capacity for runways. Several thousands of WTO conventional ballistic missiles (of ranges far above 100 km) would be required to effectively impede NATO tactical air operations in the early stages of a surprise attack. Cruise, and stand-off missiles would be better suited for such attacks, and would even be less expensive to use.

The fear of a "disarming strike by conventional tactical ballistic missiles" is therefore unfounded; no destabilizing developments are to be foreseen in this respect, and defenses against such missiles could not contribute to dampen such developments.

7.3 Destabilizing Developments by Offensive Deep Strikes Against Launchers of Tactical Ballistic Missiles

Many proponents of anti-tactical ballistic missile defenses mention two other possibilities to reduce or negate the missile threat. One is passive measures such as hardening, camouflage, or dispersal. Most of these measures would not risk destabilization. The other recommended measure is, however, attacking the ballistic missiles before they are launched. The three options are often seen as "not mutually exclusive, but rather complementary and mutually reinforcive".[4] Not in every such recommendation is the caveat being made that ballistic missile launchers deep inside the other side's territory should only be attacked after they had fired their first salvo.[5] Of course, a missile launcher is much more vulnerable than a missile in flight, and it is easier to hit because 1. it is much larger and 2. it moves much slower. Therefore it is consistent that, given the low expected efficiency of defense systems, in a military view attacks at the launchers get a higher priority. Because those launchers are generally mobile, however, targeting them puts high requirements on real-time reconnaissance of distant ground targets. Whereas in the context of several deep-strike concepts like AirLand Battle or Follow-on Forces Attack, USA and NATO are making great efforts for achieving such a capability (e.g. by side-looking radar aircraft JSTARS, by electro-optical sensors on aircraft or drones, or, in the later future and in a more general context, even by space-based radar)[6], several countermeasures (like camouflage, decoys, jamming, false transmitters etc.) will probably be able to prevent success. This holds especially for launcher positions which are at more than, say, 200 km distance. Therefore, for the next decade or so, targeting of mobile missile launchers will remain difficult in general, and especially so using ballistic missiles. Should this become possible at some time in the future, however, the resulting duel-type posture of the respective ballistic missiles would obviously be extremely destabilizing in a crisis.

7.4 Specific Properties of Anti-Tactical Ballistic Missile Systems which are Relevant for Strategic Stability

7.4.1 Anti-Tactical Ballistic Missile Defense Overlaps with Defense Against Strategic Ballistic Missiles.

As shown in 6.2, there is more similarity between defense against tactical and defense against strategic ballistic missiles than between the former and defense against aircraft. Insofar as the development and deployment of anti-tactical ballistic missile defense promotes anti-ballistic missile systems of the USA and the USSR, they contribute to increased arms race and crisis instabilities in the strategic realm in general – these underlying fears led, among other reasons, to the ABM Treaty. Specific fears of destabilization seem all the more justified today, as space-based components and weapons figure most prominently in the U.S. SDI program. Because the ranges of some tactical ballistic missiles and some strategic ballistic missiles overlap, there is not only a political connection between both types of defense, but also one that is inherent in the physical characteristics of the missiles and the interception systems.

7.4.2 Development of Anti-Tactical Ballistic Missile Defense Systems Produces an Inherent Tendency for Longer Ranges and Higher Altitudes.

As shown in 5.1, the footprint areas of local defense systems are fairly limited, especially against missiles of intermediate ranges. In a scenario where tactical ballistic missiles and defenses against them figure prominently, measures to increase footprint areas and effectiveness against missiles of longer ranges will be taken (in reality, they are already in the planning and development process). This comprises air-borne and in the future also space-borne detection and early warning systems; this also calls for ground-based interceptors with higher velocity and longer range. Whereas one could argue that strictly local defenses would not decrease stability, interceptor missiles which would reach, and fly over and into, the territory of the other side, could increase the nervousness, because they could not reliably be recognized as non-offensive. Inclusion of space components for detection and communication would increase the motives for development of space weapons; inclusion of space weapons themselves would drastically increase crisis instability. In addition, an immediate linking from a local to a global, strategic arena of conflict would result.

7.4.3 Development of Defenses Against Nuclear Tactical Ballistic Missiles Produces a Tendency for Nuclear Interception Means.

As discussed in 6.1.2.7, radiation from a nearby nuclear explosion is the only means by which – at least for the next 15 or 20 years – one could try to prevent salvage-fused nuclear warheads from exploding. This has also been openly acknowledged by the Director of the SDI Organization.[7] Deployment of new nuclear-equipped missiles in Western Europe would certainly meet strong political opposition, and the former West German Defense Minister has explicitly stated that such "anti-missile defenses must be non-nuclear".[8] The motives for nuclear interceptors do, however, arise from the physical characteristics of nuclear warheads to be defended against. Whereas plans for West European anti-tactical ballistic missile defenses may for some time exclude defense against nuclear warheads, the U.S. SDI plans certainly do not – it is the very existence of this research and development program and its inclusion of defense against nuclear shorter-range missiles which, according to former Minister Wörner, allows West European countries to concentrate on conventional ballistic missiles.[9] Another ambiguity could arise if dual-capable interceptors were used. A ballistic missile defense expert of the U.S. Army recommended using the same basic system for anti-tactical ballistic missile defense in Western Europe, and for defense of missile silos against strategic ballistic missiles in the USA; in the former role, active homing guidance and a non-nuclear interception warhead would be used, whereas for hardsite defense in the USA the same interceptor would carry a nuclear warhead and would be guided by radar command.[10] It is not clear whether the other side, even if it were able to recognize missiles flying into or over its territory as interceptor missiles, would perceive them as clearly non-nuclear in this case. It is of interest here to note that the U.S. nuclear anti-aircraft missile Nike-Hercules (now being withdrawn) – besides being dual-capable – could also be employed in a surface-to-surface role for nuclear strikes at ground targets.[11]

Another aspect is the possible use of nuclear-explosion pumped x-ray lasers for missile defense. These are actively developed in the U.S. SDI program;[12] their use on top of pop-up missiles against Soviet ICBMs targeted on the USA may require deployment in Northern Europe (but even in this case, they could not be used during the boost phase of the ICBMs).[13] If this weapon were to prove feasible, pop-up missiles carrying x-ray laser warheads against tactical ballistic missiles could be deployed in other parts of Western Europe, too.

7.4.4 Anti-Tactical Ballistic Missile Defense Systems Have Very Short Reaction Times.

As discussed in 5.4, interceptor missiles must be launched within a few seconds after a potentially threatening object has been detected and its trajectory determined. If such missiles would remain above their own territory and far away from the border during their total flight time, this would not reduce crisis stability. As stated in 7.4.2, however, there is a tendency to do the opposite. Inherent properties of defense systems produce military pressures for predelegation of launch authority to defense units in times of crisis. Even without such predelegation, it is conceivable that local commanders would launch interceptors if their instruments signal that a missile attack is underway. Of course, if the attack was real, the launching of interceptors would be justified. However, if spurious signals were produced by a computer error, or by the launch of missiles carrying surveillance sensors, or by a reconnaissance drone gone out of control, the launch of interceptor missiles on trajectories leading into the other side's territory could spell the beginning of a real shooting war. If only a couple of seconds are available for the launch decision, the possibility of launches out of sheer nervousness and/or spurious signals cannot be excluded. A self-destruct mechanism could in principle avoid offensive perceptions on the other side, but it would have to work before the interceptor missile crosses the border (or, even better, before it entered the search range of the other side's radars). Whereas this may be possible with terminal-phase interceptors deployed some 50 km from the border, it could not be utilized with late midcourse interceptors designed to intercept at several times 100 km distance.

Similar time scales would hold in case of space-based kinetic energy weapons; here the need for automated release is even more obvious. Because most of the threats to one space weapons system would result from the other one, the main theater of crisis instability would be moved into space. Should space beam weapons be deployed, the times for counter-attacks could shrink to fractions of a second, an even more menacing scenario in terms of crisis stability.

7.4.5 Longer-Range Interceptor Missiles Could Attack Satellites.

Missiles for late midcourse interception would meet their targets at several hundred kilometers altitude, i.e. in regions of space where low-orbit satellites for photo or radar reconnaissance pass regularly. In order to bring a certain mass to some altitude at the summit of a ballistic trajectory, less energy is needed than for having it orbit at that same altitude as a satellite. In principle, the burnout velocity need only be such that the kinetic energy equals the potential energy gain at the maximum altitude (for a satellite, additional kinetic energy for circling around the earth is needed). The range of altitudes and distances which can be reached by anti-tactical interceptor missiles depends on their velocity at burnout. A Type 1 interceptor, designed for terminal-phase defense, could already reach altitudes of 200 km at up to 200 km distance (see Fig. 5-5). A Type 3 exoatmospheric interceptor could cover altitudes of 1,000 km and more at up to 1,500 km distance (see Fig. 5-15). Guidance should be easier than against reentry vehicles of ballistic missiles, because satellites move along predictably accurate trajectories most of the time, are much larger, and are usually not accompanied by decoys. Insofar as non-nuclear (e.g. impact) destruction is used, and the role of satellites for ground warfare increases, the temptation to destroy low-orbit satellites early in a crisis may be strong.

Of course, satellites in higher orbits such as navigation satellites at 20,000 km or early warning and communication satellites at geostationary positions (36,000 km) would not be affected. Low-orbit satellites would only be in danger, when their trajectories cross the accessible regions around the deployment areas of the missiles. On the other hand, several observation satellites fly along trajectories which cover most regions of the globe after some time; in addition, concepts exist for deployment of ground-based anti-tactical ballistic missile defenses not only in Western Europe, but also in Israel e.g., and – in a strategic defense role – in the USA. If similar missiles would be deployed all over the Soviet Union, nearly all low-orbit satellites of the USA could be hit within a couple of hours.

If kinetic kill weapons were deployed against tactical ballistic missiles on board satellites, these satellites would by necessity have to use low orbits (i.e. between 300 and at most 1,000 km altitude). In order to have sufficient defense capacity above the appropriate regions at all times, global networks of such satellites will have to be deployed. Ground-based interceptor missiles designed against ballistic missiles in their late midcourse would provide a very effective means to attack such satellites, punching a hole into the defense which could be exploited immediately, or at some later time when it reappeared over the same region. (In a scenario of two fully deployed space weapons systems, attacks using the space weapons themselves would probably be more effective and more likely, but during a deployment phase ground-based anti-satellite attack could prove very effective.)

7.4.6 Anti-Tactical Ballistic Missile Systems Could be Used Offensively.

Of course, any defensive system could be used for offensive purposes in an indirect way, i.e. support an attack by protecting against a counterattack. Anti-tactical ballistic missile defense systems which are not strictly local and short-range (and most are not likely to fulfill these criteria, see 7.4.2), do provide new means for direct offensive operations. (Some of these have been already been mentioned.) Nuclear interceptors could be used in a secondary role against ground targets. Longer-range interceptor missiles could also provide means for attack against command, control, communications, and intelligence aircraft which fly at rear positions. This would apply to aircraft used for warning of air attack and for management of the air battle (like the U.S./NATO AWACS), to aircraft used for ground surveillance (like the planned U.S. JSTARS), and to infrared-sensor carrying aircraft used for detection of ballistic missiles (like the planned U.S. Airborne Optical System). Here, a stronger link to extended air defense exists. For some of the missions mentioned, there may be more effective means available than anti-tactical interceptors. In the assessment of stability, however, perceptions and misunderstandings have to be included. In this respect, the sheer possibility of such use, as well as the difficulty of discriminating between defensive interceptors and offensive missiles, must be taken into account.

Missiles for late midcourse interception could provide a means for attacking low-orbit satellites (see 7.4.5). Any type of space weapons for use against ballistic missiles could be directed against any space system, including weapons carriers, of the other side. Some space weapons could even be used for attacks into the atmosphere – this could affect the above-mentioned aircraft used for warning and control, missile detection, and ground surveillance. In addition, strategic command and control aircraft including supreme airborne command posts could be attacked globally. Ground attacks from space systems are also possible with some weapons types.

7.5 Prospects for Arms Race Stability

7.5.1 General Considerations

Since the real capabilities of anti-tactical ballistic missile systems of the near future would be marginal, no immediate buildup in ballistic missiles need follow on the other side. Because decisions on armaments are often driven by perceptions and worst-case assumptions, however, it is possible that missile numbers would increase if anti-tactical defenses were deployed on a large scale. On the defense side, the low efficiency is bound to produce a tendency towards longer ranges and higher altitudes of interception, as well as towards inclusion of air- and space-borne components for detection. This buildup, in turn, will produce stronger reactions on the other side. Interactions will occur between ballistic missiles and the defense systems, and between countermeasures and counter-countermeasures. It is highly unlikely that defense efficiencies will ever become so impressive that the respective other side will forego its ballistic missiles, at least in a nuclear role. Since for conventional precision attack non-ballistic missiles are more appropriate, ballistic missiles will not figure prominently in such attack plans, with or without defenses.

Whereas a general impetus to keep up with the opponent's capabilities will provide incentives for one side to increase its anti-tactical ballistic missile defense efforts, if the other does so, the main interaction will occur between one side's ballistic missiles and the other's defenses, and vice versa. How exaggerated perceptions influence strategic arguments in this field, is impressively demonstrated in articles of proponents of anti-tactical ballistic missile systems. Some authors state that in case of a Soviet "anti-ballistic missile of even limited effectiveness, NATO's capacity for exercising even its limited nuclear options could be substantially compromised".[14]

Qualitatively new impulses for offensive and defensive arms buildup are to be foreseen if space systems are included in anti-tactical ballistic missile defenses. Even if at first, only sensor satellites were used, their high strategic importance and relative vulnerability would soon lead to increased deployment of space weapons, which would be followed by counter-weapons and so on.

7.5.2 Prospects for Arms Race Stability under the INF Treaty

The ban on U.S. and Soviet ground-launched, ballistic and non-ballistic missiles between 500 and 5,500 km range strongly alters the outlook for anti-tactical ballistic missile defense. In the most significant range classes, scenarios of nuclear or conventional missile attacks become impossible, removing any motives for having defenses against them. (Some problems remain for the Soviet Union with the intermediate-range nuclear missiles of non-signatory states such as: France, Great Britain, and China.) If compensatory arms buildup takes place below 500 km, motives for defense deployment could, however, increase again; in turn, this will drive offensive enhancements. As far as aerodynamic missiles are concerned, the extended air defense version is likely to gain support; if ballistic missiles below 500 km range were to achieve greater weight, defense against them would certainly do so as well. Lacking arms limitation measures on offensive missiles, military pressures for defense systems will probably get the upper hand, all the more, because in this range class defense is relatively easier. Further factors working in the same direction are: the possible use of such missiles for anti-ship attack, and, above all, the upcoming proliferation of such missiles to other countries. This last mechanism can clearly be seen in the Middle East, where a buildup of ballistic missile capabilities is now accompanied by a thrust towards anti-tactical ballistic missile defenses.

7.6 Prospects for Crisis Stability

7.6.1 General Considerations

Insofar as insufficient defense capabilities provide momentum for deep strikes against missile launchers, there is an indirect contribution to destabilization in a crisis. Concerning direct effects, strictly local anti-tactical ballistic missile systems of limited range could be neutral. Only under the unrealistic assumptions that conventional tactical ballistic missiles could be used effectively in a surprise attack, and that defense systems against them were credible even with countermeasures, could defenses increase stability – but this is a hypothetical statement without relevance for reality. Insofar as a tendency towards intercepts at longer ranges is inherent here, destabilization is the likely future outcome of increased anti-tactical ballistic missile defense efforts. This stems from the direct offensive potential of such systems – against ground targets, against distant aircraft, against satellites –, from the difficulty of distinguishing defense interceptors from offensive missiles, and, above all, from the very short reaction times available. Aircraft with infrared sensors on board will be large, highly visible and not capable of fast maneuvers; some protection against preemptive attack is provided by their rear position, but because they would come into reach of new anti-air/anti-tactical ballistic missile defense systems, and because they would represent few but highly important targets, pressures for preemptive attack against them would rise. If one or both sides had infrared probes on missiles to be popped up on warning, these launches, even at rear positions, would be observed by the other side, also contributing to increased crisis instability. The most dangerous scenario is one in which both sides command global fleets of space weapons capable of shooting at each other on a split second notice.

7.6.2 Prospects for Crisis Stability under the INF Treaty

Some of the fears mentioned are alleviated because U.S. and Soviet ground-launched missiles from 500 to 5,500 km range will no longer be available for attack. Under these conditions, much of the pressure for long-range, high altitude intercepts would vanish, and inclusion of air, pop-up, and space components is much less imperative. As long as activities in the realm of defense against strategic ballistic missiles proceed, however, the corresponding destabilization may occur anyway, and it would become increasingly difficult, if not impossible, to keep anti-tactical ballistic missile defenses local and limited.

If one supposes that anti-tactical ballistic missile defenses were kept strictly local and limited, then the question of their effect on crisis stability has to be seen in a broader context. One has to include the whole picture of two alerted forces opposing each other, waiting for the first shot to be fired. Both sides would be characterized by high activity, and the watching of the other's ground and air space. Surveillance aircraft and drones would fly near the border, jamming transmitters would be popped up on rockets, missiles and aircraft would be flown in order to provoke the other side to turn on their air defense radars in order to list their locations, etc. Even today, this would be a highly unclear situation with many opportunities for error, misunderstanding, and overreaction. If interceptor missiles were added which would have to be launched within seconds, the situation would certainly not improve. A centralized command for real-time launch decisions could work both ways: it could prevent local commanders from inadvertent launches, but could also give rise to massive overreaction on a regional scale. On the whole, however, one would probably conclude that it is the general structures and postures of the land and air forces on both sides that produce most parts of crisis instability on the conventional tactical field. Local anti-tactical ballistic missile defenses which could not cross the border would add another layer to an already very complex situation.

In conclusion: Only if anti-tactical ballistic missile defense developments are actively restricted, can specific new kinds of instability be avoided. This requires an explicit political decision, paralleled by limits on tactical ballistic missiles. If such limitations are not imposed, long-range weapons and space systems will probably be introduced over time, in the end leading to destabilization on a qualitatively new scale.

Notes and References to Chapter 7:

1 See e.g.: B. Kubbig, (Re-)Defining and Refining the Criteria for Nuclear Arms Control – Theory and Praxis, Bulletin of Peace Proposals, vol. 16, no. 3, September 1985.

2 M. Wörner, Europa braucht Raketenabwehr, Die Zeit, 28. Februar 1986. Similarly, a U.S. Department of Defense official talked of a "devastating surprise attack on major NATO military installations" using conventionally armed SS-21, SS-12 mod., and SS-23: Statement of F. C. Iklé, in: U.S. Nuclear forces and Arms Control Policy, Hearings before the Defense Policy Panel of the Committee on Armed Services, House of Representatives, 99th Congress, 2nd Session, May 20, June 4, and 5, 1986, Washington DC: U.S. Government Printing Office, 1986, pp. 28-31.

3 A short version is: B. Morel, T. Postol, Non-nuclear Soviet Tactical Ballistic Missiles: A Threat to NATO?, Part B, in: 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; B. Morel, T. Postol, A Technical Assessment of the Soviet Tactical Ballistic Missile Threat to NATO, in: D. L. Hafner, J. Roper (Eds.), ATBMs and Western Security, Cambridge MA: Ballinger, 1988. A more detailed presentation will be given in a forthcoming report by B. Morel and T. Postol from the Center for International Security and Arms Control, Stanford University, Stanford CA. See also: D. Rubenson, J. Bonomo, The role of ATBM in NATO strategy, Survival, vol. XXIX, no. 6, pp. 511-527, November/December 1987; D. Rubenson, J. Bonomo, NATO's Anti-Tactical Ballistic Missile Requirements and Their Relationship to the Strategic Defense Initiative, Report R-3533-AF, Santa Monica CA: RAND Corporation, December 1987.

4 M. Wörner, A Missile Defense for NATO Europe, Strategic Review, vol. XIV, no. 1, pp. 13-20, Winter 1986. From the beginning, proponents of anti-tactical ballistic missile defenses have discussed attacks at the ballistic missile launchers as part of an "anti-tactical missile" programme, see e.g.: Answers by General Wickham, in: Department of Defense Authorization for Appropriations for Fiscal Year 1986, Hearings before the Committee on Armed Services, U.S. Senate, 99th Congress, 1st Session, Part 2, Army Programs, Navy-Marine Programs, Air Force Programs, February 5, 6, 7, 1985, Washington DC: U.S. Government Printing Office, 1985, pp. 776, 791. See also: D. C. Morrison, Army Fights for NATO Missile Shield, National Journal, 14 December 1985.

5 E.g. Wörner (note 4). T. Enders, in his first report on anti-tactical ballistic missiles, explicitly recommended "tactical preemption" against launchers "before they are used for the first time", using new conventional tactical ballistic missiles like the ATACMS: T. Enders, Ballistic Missile Defense as Part of an Extended NATO Air Defense (in German), St. Augustin: Sozialwissenschaftliches Institut der Konrad-Adenauer-Stiftung, Jan. 1986, p. 88. Note, however, that he revoked this view one year later and denoted a posture where both sides had their tactical ballistic missiles targeted at each other's launchers as destabilizing: T. Enders, The ATBM Conundrum – What Role for Arms Control?, in: E.-O. Czempiel, G. Krell, Arms Control in U.S. – West German Relations, to be published.

6 See e.g.: W. H. Gregory, U.S. Army, Air Force Continue Development of Joint STARS, Aviation Week & Space Technology, pp. 113-123, May 5, 1986; D. A. Boutacoff, Army Banks on Joint STARS for AirLand Battle Management, Defense Electronics, pp. 77-85, August 1986; J. d. Morocco, ATARS Competition Spurs Technology Shift from Photo to Electro-Optical, Aviation Week & Space Technology, pp. 71-77, Sep-

tember 7, 1987; G. N. Tsandoulas, Space-Based Radar, Science, vol. 237, pp. 257-262, 17 July 1987; USAF Awards Contracts to Study Space-Based Radar System, Aviation Week & Space Technology, pp. 30, September 7, 1987.

7 "In addition to the 'strategic' possibilities described here, work is proceeding on an 'underlay' defense for use on the battlefield against the shortest range ballistic missiles. These interceptors would operate below 15 kilometers altitude and may either use a 'hit-to-kill' warhead like the terminal interceptors described above, or could use a small nuclear charge. The latter option would be an effective response against salvage-fused attackers. The single kiloton-class nuclear warheads would be small enough to cause little or no damage on the ground, but would effectively disrupt the large attacking warhead before it could detonate." J. A. Abrahamson, The Strategic Defense Initiative – A Technical Summary, NATO's Sixteen Nations, vol. 31, no. 2, pp. 14-19, April 1986.

8 Wörner (note 4).

9 Wörner (note 2).

10 W. A. Davis, Jr., Regional Security and Anti-Tactical Ballistic Missiles: Political and Technical Issues (Special Report, Institute for Foreign Policy Analysis, Cambridge MA and Washington DC), Washington DC etc.: Pergamon-Brassey's, 1986, pp. 39-42.

11 T. B. Cochran, W. A. Arkin, M. M. Hoenig, Nuclear Weapons Databook, Vol. I, U.S. Nuclear Forces and Capabilities, Cambridge MA: Ballinger, 1984, pp. 287 f.

12 Report to the Congress on the Strategic Defense Initiative, prepared by the Strategic Defense Initiative Organization, Washington DC: Department of Defense, April 1987, Ch. VI-C. For an official statement on the scope of third generation nuclear weapons issued by the U.S. Department of Energy, see: U.S. Congress, Office of Technology Assessment, Anti-Satellite Weapons, Countermeasures, and Arms Control, OTA-ISC-281, Washington DC: U.S. Government Printing Office, September 1985, pp. 70 f.

13 For U.S. officials mentioning possible West European deployment of x-ray laser missiles, see: R. Bulkeley, Missile Defence in NATO Europe, pp. 131-142, in: J. Holdren, J. Rotblat (Eds.), Strategic Defences and the Future of the Arms Race, New York: St. Martins's Press, 1987. Distances from Northern Europe to Siberian ICBM silo fields are about 4,000 km; see: H. A. Bethe, R. L. Garwin, New BMD Technologies, Appendix A in: Weapons in Space, vol. II: Implications for Security, Daedalus, vol. 114, no. 3, Summer 1985.

14 Wörner (note 4). Note that Wörner discussed increases in Pershing 2 missiles as a reaction, but dismissed this, mainly "because it is not politically viable". In his second article on anti-tactical ballistic missile defense, T. Enders stated: "However, in the long run Soviet ATBMs conceivably could challenge the West's strategy *if* NATO lacks sufficient INF forces. From a purely military point of view 500 INF systems would be better than 100. And in terms of penetratibility, Pershing II is best suited for deliberate escalation." Enders, ATBM Conundrum (note 5) (author's emphasis).

8. Anti-Tactical Ballistic Missile Systems and Arms Control

The last chapter is devoted to possible limitations for anti-tactical ballistic missile systems. 8.1 takes a short look at the question how anti-tactical ballistic missile defenses relate to existing arms control treaties. Connections to other fields of arms reductions are treated in 8.2. Section 8.3 discusses several alternatives where new limits could be defined 1., to keep the ABM Treaty alive, and 2., to prevent destabilizing developments in the field of anti-tactical ballistic missile defense. Recommendations for comprehensive arms limitation and reduction measures are given in 8.4.

8.1 Existing Arms Control Treaties

8.1.1 The ABM Treaty

The ABM Treaty is the most important treaty regarding anti-tactical ballistic missile defense systems. Concluded by the USA and the USSR in 1972, it does not formally restrain ballistic missile defense activities by third countries. West European NATO countries as well as East European WTO countries have, however, expressed their commitment to the continuing functioning of this treaty.[1]

Since the subject has been covered to a significant extent in the literature, only the most important aspects will be repeated here in short terms:[2]

- There is a considerable range overlap between some strategic ballistic missiles, against which defenses are only allowed at one area under the treaty, and intermediate-range missiles, which are formally outside the scope of the ABM Treaty.[3] Some submarine-launched strategic ballistic missiles have ranges of 4,000, others of 2,400 km; their flight trajectory, and the process of their interception, do not differ from those of land-based intermediate-range ballistic missiles of comparable range. Whoever aquires a defense capability against the latter, automatically gets one against the former. Both sides could not deploy such defenses except at the one allowed ABM area (Art. I and III), and development and tests would have to take place at the allowed test ranges (Art. IV).
- The ABM Treaty prohibits giving non-ABM systems ABM capabilities, and testing them in an ABM mode (Art. VI). Originally aimed against using upgraded air defense systems as ABM systems, this article would apply equally to such upgrading of anti-tactical ballistic missile systems. In a unilateral statement to the treaty, the USA found this applicable e.g. to interceptor tests against a target vehicle with characteristics of a strategic ballistic missile flight trajectory (Unilateral Statement B). This would of course hold in the case of interceptor tests against intermediate-range ballistic missiles.
- The ABM Treaty also bans ABM systems and components outside of the national borders (Art. IX); ABM-capable defense systems deployed e.g. by the USA in Western Europe (or in cooperation with West European states) would violate the treaty.

- ABM systems and technology may not be transferred to other countries (including blueprints etc.) (Art. IX and Agreed Statement G). Cooperation of the USA or the USSR with European states in developing defense systems which would have a capability against strategic ballistic missiles, would violate the treaty if technology and knowledge is transferred to those third countries.
- The ABM Treaty bans ABM systems for simultaneous launch of more than one interceptor from each launcher, rapid reload of interceptors, and interceptors with more than one intercepting warhead (Art. V and Agreed Statement E). Concepts with several interceptor missiles on one mobile launcher, or of e.g. three exoatmospheric warheads – able to attack intermediate-range missiles – on top of one interceptor rocket, contradict the provisions of the treaty.
- The ABM Treaty bans land-based ABM systems which are mobile (Art. V). Anti-tactical ballistic missile systems are normally designed to be mobile. Insofar as they would be capable against ballistic missiles of 2,000 km range and above (and they would belong at least partly to either the USA or the USSR), they would violate the treaty.
- The ABM Treaty prohibits any ABM systems or components which are air-based or space-based, even including development and tests (Art. V). Any such component of an anti-tactical ballistic missile system (be it sensors or weapons) would automatically also have some capability against strategic missiles. Therefore, they would violate the treaty.[4]

As the ABM Treaty contains no formal obligation for third states, the completely independent development of defense systems against ballistic missiles of any range could legally be done by e.g. Great Britain, France, or the Federal Republic of Germany (or e.g. by Czechoslovakia or the German Democratic Republic). Of course, development of defenses against missiles of ranges above about 1,500 km would remove the basis on which any such state could demand adherence to the ABM Treaty from its signatory parties.

For tactical ballistic missiles clearly below the range of strategic missiles, i.e. below about 1,500 km, the ABM Treaty does not apply. Here, even the signatory states are legally free to develop, test, and deploy defense systems.But because there is a continuous variation of missile velocity with range, any development and test against tactical ballistic missiles of ranges above 500 or 1,000 km, will be perceived by the respective other side as providing a capability against (at least some) strategic missiles.[5]

8.1.2 Other Treaties

The Outer Space Treaty of 1967 bans deployment of nuclear weapons in orbit (Art. IV).[6] Any type of nuclear explosive device for anti-tactical ballistic missile use, if deployed on a satellite, would violate that rule. (Note that nuclear warheads on top of ballistic missiles are not included here.) Taking the obligations of Art. III seriously, namely that the activities in outer space shall be carried out in the interest of maintaining international peace and security, and promoting international co-operation and understanding, this stipulation would call for a ban on anti-satellite and space weapons, as well as for a limit on military uses of satellites. Interceptor missiles against tactical ballistic missiles which could attack satellites would contradict the intent of this treaty. The same would hold for space-based interceptor weapons.

The Treaty between the USA and the USSR on the Elimination of their Intermediate-Range and Shorter-Range Missiles (INF Treaty) of 1987 explicitly exempts ground-launched ballistic missiles developed and tested solely to intercept and counter objects not located on the surface of the earth from its provisions (Art. VII (3)).[7] The only limit concerning anti-tactical ballistic missile systems which derives from this treaty is therefore that ground-based interceptor missiles may not be tested against ground targets at ranges between 500 and 5,500 km.

8.2 Connections to Other Fields of Arms Limitations or Reductions

The INF Treaty of 1987 directly affects the question of anti-tactical ballistic missile defense. By removing and destroying all ground-launched – aerodynamic and ballistic – missiles with ranges from 500 to 5,500 km of the USA and the USSR, most arguments for development of anti-tactical ballistic missile defenses become obsolete. This holds especially for the fear of a surprise attack using conventional ballistic missiles. Therefore, an agreement banning defense systems against ballistic missiles above 500 km range should be possible without much resistance. There are, however, several problems.

One is the continuing existence of tactical and intermediate-range ballistic missiles of third countries like France, Great Britain, or the People's Republic of China. These countries would have to be included in a new agreement banning ballistic missile defense in general, and this would probably require reductions in their offensive missiles. If the USA and the USSR succeed in drastic reductions of their nuclear offensive arsenals, including the weapons of these countries will be easier.

Another difficulty will arise out of the tendency of other countries to obtain their own ballistic missiles. If this development would proceed unimpeded, it would be difficult to have a ban on defenses against them. Limits for tactical ballistic missiles will have to include several countries to remain effective.

A third problem is the quest for countrywide ballistic missile defense, including new kinds of space weapons, which is manifested in the U.S. SDI program. At some stage in the development and testing process, the ABM Treaty will be at stake. Certainly, no new agreement encompassing even stricter regulations concerning defense against ballistic missiles, and having third parties participating, will be possible if even the ABM Treaty obligations cease to be honored by its signatory states. Besides this general link, there exist several specific connections with the field of anti-tactical ballistic missile defense via the commonality of sensors and weapons.[8] A comprehensive agreement banning anti-tactical ballistic missile defenses would necessarily include all technologies which are presently under development in the U.S. SDI program.

A special problem which could create strong pressures for extension of air defenses to reach into space, is posed by the possible military use of transatmospheric vehicles. They could fly aerodynamically at higher altitudes than today's high-altitude aircraft, and could also rise to low earth orbits, flying on ballistic or satellite trajectories for some time. Whereas it is doubtful if such carriers would provide significant new military capabilities which are not now covered by intercontinental ballistic missiles on the one hand, and by bombers on the other hand,[9] it is highly improbable that a ban on anti-tactical ballistic missile systems, as well as a ban on anti-satellite weapons, could be kept alive if they would be deployed by the military on a larger scale.

The INF Treaty leaves a loophole below 500 km range. If the "loss" of the missile capacity above that range is compensated for by increased deployment of ballistic missiles below 500 km, perceived threats at least in the countries near the NATO-WTO border will rise, and pressures for developing defenses against these short-range missiles will increase accordingly.

Another problem concerns non-ballistic missiles below and above the 500 km range. Whereas ground-based aerodynamic missiles above 500 km of the USA and the USSR are banned by the INF Treaty, no such obligation formally holds for other states. As to sea or air-launched missiles, even the USA and the USSR are not restricted. Nuclear cruise missiles of strategic range can be included in the strategic reduction agreement; nuclear cruise and stand-off missiles of shorter ranges, and possibly belonging to third parties, have to be dealt with in additional agreements. Because the chances for effective defense against nuclear missiles are so low, progress in this field may not be a stringent requirement for limits on anti-tactical ballistic missile defenses. On the other hand, aerodynamic vehicles equipped with precision-guided conventional warheads or submunitions are assigned an increasing role in many concepts for strengthening military offensive effectiveness by deep strikes. If this development proceeds unimpeded, pressures for enhanced defenses against aerodynamic missiles will inevitably rise (as they have done already), in turn increasing the need for more, and more capable, missiles. Whereas the limits on anti-tactical ballistic missile defense which will be proposed below do not strongly hamper defenses against aerodynamic missiles, in order to avoid ambiguities and misperceptions, and in order to prevent a destabilizing arms race in the field of non-ballistic missiles and defenses against them, limits should be introduced here too. Because of the complex relationships which exist with aircraft and land forces, such limits have probably to be part of a general reduction, and restructuring to more defensive postures, of the military forces in Europe in general.

Finally, the navies have to be included into these considerations. Ballistic missiles are up to now not regularly foreseen to be targeted against ships at sea, mainly because of uncertainty in location: in 10 minutes flight time over 1,000 km, a vessel could have moved by 5 to 10 kilometers, i.e. even outside the damage area of a nuclear warhead. With maneuvering warheads and terminal guidance, this could over time change, increasing pressures for naval defenses against tactical ballistic missiles. Long-term limits on anti-tactical ballistic missile defenses therefore would have to include naval systems, and would have to be augmented by limits on ballistic missiles which could be used at sea. As in the case of land warfare, separation from defense against aerodynamic missiles is possible with the criteria given below, but in order to prevent ambiguities, limits on such missiles and defenses should be added. Similarly, this would probably be part of general reduction and disengagement measures on sea.

8.3 Possible Limits for Anti-Tactical Ballistic Missile Systems

8.3.1 Accompanying Limits Concerning Tactical Ballistic Missiles

Of course, any reduction of tactical ballistic missiles would reduce military pressures for development of defenses against them, and would thus alleviate the conclusion of an agreement banning such defenses (see 8.2). In addition, specific measures could support a ban on defense systems. Some of these include: limits on the number of tests of tactical ballistic missiles; limits on the activity of systems which could potentially be used for defenses during such tests (like limits on radar activity, and limits on observation aircraft).

8.3.2 Where to Draw the Line?

Between air defense systems and systems directed against strategic ballistic missiles exists a grey area of considerable latitude. At the lowest ballistic missile ranges (below about 200 km), air defense-like interceptors may provide some capability; at intermediate ranges (above 2,000 km), explicit overlap with defense against strategic missiles exists. Limits on anti-tactical ballistic missile defense could modestly try to prevent ambiguities concerning the ABM Treaty, or could more ambitiously try to encompass short-range missiles too. The first, modest, approach would divide allowed anti-tactical ballistic missile defense from forbidden defense against strategic missiles by defining effective limits at missile ranges of, say, 2,000 km. This procedure would not create new international law, and could be agreed upon bilaterally between the USA and the USSR as an amendment to the ABM Treaty. Whereas this could be a viable short-term solution, it brings with it several opportunities for misperceptions, and would probably sooner or later be undermined by third country developments. A more ambitious, and more basic, solution would draw the line between air defense and defense against ballistic missiles of most ranges (depending on the criteria chosen, some missiles of the shortest ranges may be excluded, see below). This would require participation of several other states already in possession of, or being capable of developing, tactical ballistic missiles and defense systems against them. It would avoid nearly all misperceptions, and could remain effective for a significantly longer time (it would have to be complemented by parallel limits on offensive missiles, see below).

Because attack aircraft form an important part of the offensive capabilities of the military forces today, it does not seem advisable to impose limits which would significantly reduce the effectiveness of local air defense systems. If the role of aerodynamic missiles increases, as is foreseen in many plans, trying to introduce limits on defenses against them will be equally problematic. Both, aircraft and aerodynamic missiles, cannot fly at altitudes above about 30 km, and are limited to velocities of about 1 km/s (Mach 3-4) (with the possible exception of future transatmospheric vehicles, see below). These quantities suggest themselves as a limiting line for separating allowed defense systems from banned ones. Accordingly, defense against short-range ballistic missiles not exceeding values like these have to be allowed in parallel. This roughly corresponds to a ballistic missile range of 200 km, which is proposed here as the limit for defense systems as well as for ballistic missiles themselves.

8.3.3 Technical Evaluation of Possible Limits on Ground-Based Interceptor Systems

8.3.3.1 Ban on Interceptor Maneuverability at High Altitudes

Both aircraft and air defense missiles rely on aerodynamic wings and control flaps for lift and maneuvers. This works at altitudes of up to about 25 km. Interceptors intended to be guided to their targets at higher altitudes need non-aerodynamic mechanisms to change their course. Sidewards-directed forces can be produced either by slight changes of the direction of the exhaust gases while the rocket motor is still burning (thrust vector control), or by special lateral thrusters (normally located in the upper parts of the missile). The last possibility works also after burnout of the main motor. (This mechanism is also used in exoatmospheric interceptors and anti-satellite weapons.) For interceptor missiles against ballistic missiles, which require higher maneuverability, air density at 25 km may already be too low (the U.S. FLAGE missile, e.g., designed for intercepts at 15 km, has lateral thrusters). A ban on such control mechanisms would exclude almost any interception of ballistic missiles, because in order to achieve acceptable keep-out altitudes and footprint areas, a capability to intercept at higher than 25 km altitude is regularly required. Only last-resort interceptors in the low atmosphere would remain, which would render defense against ballistic missiles ineffective; such a measure would, at the same time, not affect defense against aircraft and aerodynamic missiles.

The non-existence of mechanisms for thrust vector control or of lateral thrusters can, however, only be verified by inspection of the interceptor missiles themselves; possibly even shrouds would have to be removed. It is not clear if such a degree of intrusiveness will be acceptable to all states which would have to be members of a treaty limiting anti-tactical ballistic missile systems. Besides being very intrusive, such an inspection regime would also be fairly expensive.

8.3.3.2 Ban on Defense against Ballistic Missiles Altogether

If accompanied by a ban on testing, a prohibition of defense systems against ballistic missiles of any range could be a possible solution, which would not touch upon defense against aerodynamic vehicles. (Such an approach has been proposed with the idea of deleting the word "strategic" from Art. II of the ABM Treaty.[10]) This approach would be comprehensive; in order to prevent circumventions, it would have to be amended by bans on testing against vehicles which simulate ballistic missiles in the reentry phase (e.g., supersonic testing vehicles launched from aircraft). Verification using national technical means could be relied upon for defense against larger ballistic missiles (i.e., with ranges of 500 km and higher); in the short-range region, however, this comprehensive ban would probably require cooperative verification with a considerable amount of intrusiveness. Under such a regime, e.g., even tests of defenses against artillery rockets were forbidden. Such rockets may be less than one meter long, with ranges of 20 km and maximum altitudes of less than 10 km. Of course, such defenses would be of doubtful utility – and currently none seem to be planned for in any army –, so a lack of verification capabilities may still be adequate. Such a comprehensive ban would, however, touch upon armaments for short-range warfare, without real necessity. The problems for stability in the realm of conventional, and short-range, weapons have to be solved by a specific approach. In order to prevent destabilizing developments in the field of anti-tactical ballistic missile defenses, it is not urgent to include the shortest ranges.

8.3.3.3 Limits on Interceptor Size or Mass

For a given mass of an intercepting warhead (and at a given state of missile technology), the velocity attainable at burnout, and thus the maximum interception range, depend on the fuel mass on board, which is directly related to the size, and the mass, of an interceptor missile. Geometrical measurements using national technical means are possible down to sub-meter resolutions, so a limit on interceptor length and diameter (or volume) would not present a verification problem. The number of stages as well as masses of interceptors could either be established cooperatively,[11] or could be inferred by observing test flights. Such criteria could e.g. be used to differentiate between nuclear, long-range interceptors of ABM systems and conventional, short-range interceptors of anti-tactical ballistic missile systems.[12]

Such an approach would impose efficient limits on traditional interceptors (i.e., with nuclear, or conventional explosive, warheads of masses in the 50 to 1,000 kg region). It would, however, leave totally open tests and deployment of interceptors with small, direct-hit warheads which could weigh as little as 30 or even 10 kg. With such a warhead, even a 5 m long missile could achieve intercepts in outer space, at distances of more than 1,000 km (see the Type 3 missile in 5.1.5.3). Therefore, other than stopping development of defense systems, limits of this kind would rather provide incentives for increased pace in creating modern, small warhead, interceptors.

8.3.3.4 Limits on Interceptor Acceleration, Velocity, Altitude, or Range

It is possible to design limits for kinematic properties of interceptors in such a way that interception of strategic ballistic missiles is severely constrained whereas air defense will only be minimally affected. Several sets of figures have been mentioned for such purposes. One is: acceleration, below 50 times the gravity acceleration of the earth (500 m/s^2); velocity, below 1.4 km/s; altitude, below 30 km; range, below 100 km.[13] Other authors propose limits of about 2 km/s for interceptor velocity, and 40 km for interceptor altitude, in tests of anti-tactical ballistic missile defenses.[14] A third set combines 2 km/s and 40 km with a maximum acceleration of 100 times the earth gravity acceleration (1,000 m/s^2).[15] Verification should be possible using national technical means; it could be augmented by cooperative measures.[16] Whereas limits like these are certainly appropriate to draw a line between air defense and defense against strategic ballistic missiles, they would have to be very finely tuned if defense against tactical ballistic missiles of less than 1,500 km range is to be banned, while air defense is not to be impeded. This would greatly increase the verification difficulties. As part of a limitation package, however, they could be very effective. In particular, velocity, altitude and range criteria could reduce fears and misperceptions as to possible offensive uses of such missiles against satellites or ground targets.

8.3.3.5 Limits on Altitude and Velocity of Target Objects

Insofar as any new military system is only credible (to the own military as well as to the other side) if it has been tested successfully several times under conditions which simulate real ones, a ban on testing of defense systems against certain types of objects would effectively support a ban on the existence of such defenses. A traditional U.S. Department of Defense definition of the phrase "tested in an ABM mode" of Art. VI of the ABM Treaty has been that a target reached an altitude above 40 km and a velocity greater than 2 to 4 km/s.[17] This criterion does not, however, preclude tests against objects of higher velocity which are launched from aircraft and remain below 40 km. One author has proposed a change of this criterion in such a way that tests against objects which had either achieved a speed of more than 3 km/s or an altitude of greater than 60 km at any point of their trajectory would be banned.[18] Others use the same velocity criterion with a 40 km altitude limit.[19] The velocity criterion alone would exclude defense against tactical ballistic missile of above about 1,200 km range; the altitude criterion (40-60 km) alone would exclude defense against ballistic missiles of more than about 200 km range (see Table 3-1).[20] For keeping the ABM Treaty valid, this combined criterion is certainly appropriate. In order to reliably prevent misperceptions as to defense capabilities against missiles of 1,000 km range, however, a velocity criterion which better matches the altitude one seems more advisable. This could amount to

1.5 km/s, which would allow defense tests against missiles of up to 200 km range (or objects simulating such missiles), but not above. In order to sharpen the distinction from air defense systems, it seems also appropriate to stay with the lower altitude criterion of 40 km. Values less than that would interfere with the ability to intercept high-flying aircraft like the U.S. SR-71 which has a ceiling of 30 km. (Both altitude criteria would hamper interception of future trans-atmospheric vehicles; but since these would sometimes fly even at satellite altitudes, demanding freedom to intercept them precludes a ban on anti-satellite weapons too. This problem would better be tackled by limits which affect the offensive potential of such vehicles.)

8.3.3.6 Limits on Radar Systems

As demonstrated in 5.1.5 and 6.1.1, mobility reduces the radar search range for longer-range ballistic missiles already to levels where a defense capability becomes questionable (while at the same time, search ranges for aircraft may be hundreds of kilometers). One could use this fact and limit the power-aperture product of any mobile radar to a value typical of a modern air defense system (e.g. 50,000 Wm^2 of the U.S. Patriot system)[21]. Similar limits on fixed radars would have to be agreed in parallel, effectively banning large phased-array radars, maybe with the exceptions which are presently allowed for USA and USSR by the ABM Treaty. Because large fixed radars at forward positions would be very vulnerable, formal renunciation should not provoke much military resistance. Verification of such limits on radars is possible by national technical means (i.e., mainly by observation, and electronic intelligence, satellites). (Note that the ABM Treaty bans phased-array radars with a power-aperture product of more than 3,000,000 Wm^2 except at the allowed deployment and test areas, and except those used for early warning, space tracking and for verification.[22])

8.3.4 Technical Evaluation of Possible Limits on Air- and Spaceborne Systems

8.3.4.1 Limits on Infrared Detection Aircraft

Airborne optical detection systems for reentry vehicles which are part of ballistic missile defense systems are banned by Art. V of the ABM Treaty, because they would be air-based ABM components. There is no significant difference between airborne optical systems for detection of strategic, as opposed to tactical, ballistic missiles; in order to keep the ABM Treaty viable, a ban on the use of such aircraft against tactical missiles too, is necessary. Observing high-altitude aircraft continuously patrolling is not a problem, and the bases would be known to the respective other side. Using cooperative verification schemes, stringent limits on infrared sensor systems could be imposed, like limits on the number of detector elements. However, this would be quite intrusive. Using national technical means only, non-use of such aircraft with tests of tactical ballistic missiles could be verified. Another property measurable by national technical means is the size of openings for the optical system, which can be determined to about 0.1 m accuracy. In order not to degrade the optical resolution, curved windows which could be matched to appear as parts of the fuselage are excluded; the optical system has to look through an opening pointing partly upwards, and thus being regularly visible to satellites. The size of this opening is directly related to the size of the light-collecting optics, which in turn bears directly on the detection range attainable (see 4.1.3.1). If for high-flying aircraft the size of any window or opening which could be opened during flight, were limited to the size of present windows of civilian jetliners (i.e., about 0.1 m^2 area), detection ranges would be reduced by a factor of at least 8 as compared to the Airborne Optical System (with an optics area of about 0.8 m^2; if the fact is taken into account, that normally the opening will be larger than the optics, the reduction will be stronger). With such a limit on the allowed opening area, detection ranges would shrink from above 1,000 km to below 200 km, which is nearly of the same order of magnitude as with mobile radars, and would not warrant the additional expense for infrared detection aircraft. A supplementary limit could be the maximum number per area – deployed and in the air – of high-flying patrol aircraft. This number would have to be very low to be effective, however (maybe one aircraft in the air per side only in the whole of Europe), and may conflict with military requirements for photo-reconnaissance flights. If aircraft with larger openings were to be used for civilian, e.g. research purposes, notification and inspection could prevent misunderstandings.

8.3.4.2 Limits on Infrared Detecting Satellites

One can transfer many of the considerations made with airborne infrared sensors to satellites in low orbits looking roughly horizontally for the long-wave infrared radiation of reentry vehicles during their midcourse flight. As space-based components of ballistic missile defense systems, they are banned by Art. V of the ABM Treaty. In order to have a workable detection system, a sizeable fleet would have to cover the globe, and the satellites would be easily observed. Here, a numerical limit on low-orbit satellites could be helpful. The size of openings could be limited in a similar fashion as with aircraft; other functions of observing the earth and its atmosphere in the visible or infrared region would not be affected significantly, because radiation from these sources is much stronger, and optics can be smaller anyway.

More difficult is the problem of short-wave infrared detection by high-orbit (i.e., mostly geostationary) satellites. Here, a number of such satellites for early warning of strategic ballistic missile attack already exist; their optics are currently large already, and drastic upgrading is not necessary for detecting tactical ballistic missiles (the short-wave infrared emitted power of which is only a factor of 4 to 10 lower, see Table 4-3). Part of this early warning function has a stabilizing role, numerical limits at about the present number could not prevent use for detection of tactical ballistic missiles, and limits on the communications would be extremely difficult to agree upon and to verify, so no regulations seem advisable here.

8.3.4.3 Limits on Air- and Spaceborne Weapons

The provision of the ABM Treaty banning ABM components and systems which are air- or space-based has to be extended to defense against tactical ballistic missiles, if the treaty is to remain effective. A ban on interceptor missiles against ballistic missiles, launched from aircraft, including a ban on testing, would be verifiable using national technical means. The same would hold for tests and deployment of satellites equipped with missiles or electromagnetically launched projectiles. Beam weapons on board satellites could also be verified by national technical means. Tests of nuclear-explosion driven weapons in the atmosphere or in space are of course easily observable.

Whereas a ban on air-launched interceptors should be included in an agreement limiting anti-tactical ballistic missile defense systems, bans on space weapons directed against ballistic missiles would better be concluded in the context of a general ban on space weapons (see 8.4.3).

8.4 Recommendations for Comprehensive Arms Limitation and Reduction Measures Related to Anti-Tactical Ballistic Missile Systems

Summarizing the discussion of 8.1 to 8.3, several measures will now be recommended to avoid instabilities associated with anti-tactical ballistic missile systems specifically, and to reduce threats and threat perceptions by ballistic missiles generally. The USA and the USSR could introduce the specific limits on very short notice by amendments to the ABM Treaty; in order to keep such limits effective, worldwide participation of all states which possess or develop ballistic missiles should be strived for.

Most recommendations can in principle be realized within a relatively short time. Measures which would go further could no longer be confined to missiles and missile defenses. They would rather have to encompass many aspects of the general structures of armies, air forces and navies, and will have to be part of a generic process of nuclear disarmament and conventional stabilization.

8.4.1 Specific Limits for Systems and Components which Could be Used for Anti-Tactical Ballistic Missile Defense

The verification possibilities for the limits on air or missile defense systems which will be proposed in this section have been discussed in 8.3. Most limits can be verified using high quality national technical means, including observation of tests. In a few cases, verification could be made easier by some cooperation between the sides, such as agreed test ranges and prior notification of tests.

For a comprehensive ban, defense systems against ballistic missiles of more than 200 km range and their components should be banned, including development and testing. (For the USA and the USSR, exceptions could hold for the allowed ABM deployment areas and test ranges.)

- Specifically, any interception of an object should be banned which had at any point of its trajectory an altitude of above 40 km, or a velocity above 1.5 km/s.
- Ground or air-launched interceptor missiles may not exceed the following limits: acceleration, 500 m/s^2; velocity, 1.5 km/s; altitude, 30 km; range, 100 km.
- The power-aperture product of mobile radars may not exceed 50,000 Wm^2.
- Aircraft flying at altitudes above 8 km may not have an opening of more than 0.1 m^2 area which can be opened during flight. (Exceptions would apply for low numbers of research aircraft after agreed notification and inspection procedures.)
- Satellites flying at altitudes below 5,000 km all the time may not have openings of more than 0.1 m^2 area, except for a low number (maybe 10) per side with agreed procedures for notification and inspection.

8.4.2 Limits on Ballistic Missiles

The best means of supporting a ban on defense against ballistic missiles above 200 km range would of course be a total ban on such missiles themselves. Because several countries already possess ballistic missiles with ranges above 200 km, and some see their national existence based on a nuclear second-strike capability secured by those ballistic missiles, a differentiated and phased approach should be taken.[23]

The USA and the USSR should effect deep reductions on their strategic nuclear weapons. They should extend the ban on ground-launched nuclear missiles down to 200 km range.

The other nuclear powers should join the reductions as soon as the deep reductions of the U.S. and Soviet arsenals are being made.

A non-proliferation treaty for ballistic missiles above 200 km should be concluded internationally, similarly to the Non-Proliferation Treaty for Nuclear Weapons.[24] In such an agreement the states having military ballistic missiles with more than 200 km range would agree not to provide such missiles and their technology to other states, and to reduce their arsenals. The states not yet having such missiles would take the obligation not to acquire or develop them. Specific rules would have to govern civilian space technology, like international inspection of high-altitude sounding rockets etc.

In order to reduce threat perceptions, and to lay the ground for their eventual abandonment, corridors or zones free of ballistic missiles above artillery range (i.e., above 30 to 40 km) could be helpful in crisis regions and in regions where large forces oppose each other.

8.4.3 General Ban on Space Weapons

Unlike the situation with nuclear missiles, no weapons in space are deployed at present, and ground- as well as air-based space weapons are still in their infancy. Therefore, a general ban on weapons deployed in space or directed against space objects could be concluded on short notice. Such an agreement would have to include development and tests, and appropriate measures to avoid ambiguous situations in space (rules of the road etc.).[25] In order to keep such a ban alive, limits on other military activities in space have to be concluded too.[26] Avoiding misperceptions concerning illegal weapons research and development would require specific limits on certain activities (e.g. on sizes of mirrors and powers of lasers).[27] Concerning hybrid aerospace vehicles, stringent limits for their military uses should be agreed upon before they are developed.

8.4.4 Limits on Non-Ballistic Missiles

If bans on ballistic missiles with ranges above 200 km, and on defenses against them, remain isolated events, there is the predictable danger that they will be circumvented by other technologies, and thus be undermined in the medium and long term. In order to prevent this from happening, and to prevent destabilizing developments on their own, limits on aerodynamic missiles are required. To match the ballistic missile limits, a ban on aerodynamic ones of range above 200 km seems consequential.

Notes and References to Chapter 8:

1 But note that some governments keep open the possibility of the abrogation of the ABM Treaty in the longer term, if strategic defense systems were to be deployed. The West German Government, e.g., in its declaration toward the U.S. SDI project, stated that "adherence to the ABM Treaty has priority in the short and medium term": H. Kohl, Erklärung der Bundesregierung zur Strategischen Verteidigungsinitiative der Vereinigten Staaten von Amerika, Deutscher Bundestag, Plenarprotokoll 10/132, 18. April 1985.

2 See e.g.: H. G. Brauch, Anti-Tactical Missile Defense – Will the European Version of SDI Undermine the ABM Treaty?, AFES-Paper No. 1, Stuttgart: Institut für Politikwissenschaften, Universität Stuttgart, July 1985; T. K. Longstreth, J. E. Pike, J. B. Rhinelander, The Impact of U.S. and Soviet Ballistic Missile Defense Programs on the ABM Treaty, Washington DC: National Campaign to Save the ABM Treaty, March 1985, pp. 34-37, 54-56; R. Bulkeley, H. G. Brauch, The Anti-Ballistic Missile Treaty and World Security, Mosbach: AFES-PRESS, 1988, pp. 34-41; I. H. Daalder, J. Boutwell, TBMs and ATBMs: Arms Control Considerations, in: D. L. Hafner, J. Roper, ATBMs and Western Security, Cambridge MA: Ballinger, 1988. For the text of the Treaty and its Appendices, see e.g.: Longstreth et al.; Arms Control and Disarmament Agreements, Washington DC: U.S. Arms Control and Disarmament Agency, 1982.

3 Whereas the USSR has from the beginning insisted that missiles targeted at her from forward bases were strategic, which the USA strictly opposed, in the SALT I treaties strategic ballistic missiles were defined as either land-based ones having ranges above 5,500 km, or sea-launched ones without any lower range limit.

4 The assertions of the present U.S. government since 1985, that the ABM Treaty does not apply to exotic detection and interception technologies, are obviously not well founded in the history of the SALT I talks, see: S. Nunn, Interpretation of the ABM Treaty, May 19, 1987, reprinted in: The ABM Treaty and the Constitution, Joint Hearings before the Committee on Foreign Relations and the Committee on the Judiciary, U.S. Senate, 100th Congress, March 11, 26, and April 1987, Washington DC: U.S. Government Printing Office, 1987; see also: Sam Nunn on the Senate Floor, ABM Reinterpretation 'Fundamentally Flawed', Arms Control Today, pp. 8-14, 38, April 1987. Anyway, to avoid undermining the treaty, cooperative definitions of categories like "ABM component" or "development" are necessary, see: Longstreth et al. (note 2).

5 This mechanism can be seen e.g. in the U.S. perception of the capabilities of the Soviet air defense systems SA-10 and SA-X-12 (the latter is comparable to the U.S. Patriot system); they are assigned a capability against tactical ballistic missiles, and it is stated that they "may have the potential to intercept some types of strategic ballistic missiles": Soviet Military Power 1987, Washington DC: U.S. Department of Defense, 1987, pp. 50, 60-61.

6 See also: H. van Gool, D. von Houwelingen, E. Schoten, Assessing ATBM, Boerderijcahier 8703, Enschede: University of Twente, Centre for the Study of Science, Technology and Society "De Boerderij", September 1987, pp. 140-142. For the treaty text, see: Arms Control ... (note 2).

7 For the text of the treaty and its associated protocols, see e.g.: Treaty between the United States of America and the Union of Soviet Socialist Republics on the elimination of their intermediate-range and shorter-range missiles, Message from the President of the United States, 100th Congress, 2d Session, Senate, Treaty Doc. 100-11, Washington DC: Government Printing Office, 1988.

8 In this context, it is interesting to note that the most recent report of the Strategic Defense Initiative Organization explicitly denies that the INF Treaty removes the need for anti-tactical ballistic missile developments. Among the reasons given are: continuing existence of short-range ballistic missiles, possible use of Soviet intercontinental and sea-launched ballistic missiles against West European targets, intermediate-range ballistic missiles of other countries: Report to the Congress on the Strategic Defense Initiative, prepared by the Strategic Defense Initiative Organization, Washington DC: Department of Defense, April 1988, pp. 3-19 – 3-20.

9 See e.g.: S. W. Korthals-Altes, The Aerospace Plane: Technological Feasibility and Policy Implications, Report No. 15, Cambridge MA: Program in Science and Technology for International Security, MIT, July 1986.

10 Prepared Statement of J. B. Rhinelander, p. 39, in: Review of ABM Treaty Interpretation Dispute and SDI, Hearing before the Subcommittee on Arms Control, International Security and Science of the Committee of Foreign Affairs, House of Representatives, 100th Congress, First Session, February 26, 1987, Washington DC: U.S. Government Printing Office, 1987.

11 This could be done by mutual data exchange and by weighing without actually inspecting missiles, similarly to the procedures agreed upon in the Protocol on Verification of the INF Treaty, see note 7.

12 This argument is expanded in: H. Lin, Evolving the ABM Treaty Towards the Year 2000, Cambridge MA: MIT Center for International Studies, May 23, 1986, Section 6.3.1.

13 Lin (note 12), Section 5.3.2.

14 Longstreth et al. (note 2), p. 75.

15 Daalder/Boutwell (note 2).

16 Lin (note 12), Section 5.3.2.

17 This was only the position of the U.S. Department of Defense; no inter-agency position was reached. See: Longstreth et al. (note 2), p. 56.

18 Lin (note 12), Section 6.2.1.

19 Daalder/Boutwell (note 2).

20 Note that Lin only used vacuum trajectories without boost phase in his calculations, resulting in significant deviations from reality for short ranges: Lin (note 12), Section 6.2.1.

21 Daalder/Boutwell (note 2).

22 Agreed Statement F, ABM Treaty (note 2).

23 As a possible intermediate option in Europe, the following set of restrictions has been proposed: a ban on tactical ballistic missiles above 300 km range; a numerical limit of 300 per side for tactical ballistic missiles between 100 and 300 km; a ban on such missiles in a region lying 100 km on either side of the alliance border in Central Europe: Daalder/Boutwell (note 2). A corridor free of theatre nuclear weapons having 150 km depth on each side has already 1982 been proposed by the Palme Commission: The Independent Commission on Disarmament and Security Issues, Common Security, London: Pan Books, 1987. The parties SPD of the FRG and SED of the GDR have proposed a corridor of the same width free of nuclear weapons and nuclear-capable systems: Im Wortlaut – Angriffsfähigkeit beseitigen, Frankfurter Rundschau, 22 October 1986.

24 For overviews on third world countries having or developing ballistic missiles, see: A. F. Manfredi, Jr., R. D. Shuey, R. M. Preece, R. G. Sutter, W. H. Donnelly, Ballistic Missile Proliferation Potential in the Third World, Report No. 86-29 SPR, Washington DC: Congressional Research Service, Library of Congress, April 24, 1986; A. Karp, Controlling the Spread of Ballistic Missiles to the Third World, Arms Control, vol. 7, no. 1, pp. 31-46, May 1986; A. Karp, The frantic Third World quest for ballistic missiles, Bulletin of the Atomic Scientists, pp. 14-20, June 1988. Note that the member states of the Western Economic Summit group have agreed to limit the export of technologies for ballistic missiles and unmanned aerodynamic vehicles, and that they have asked other countries to join: D. M. North, Seven Nations Curb Nuclear Weapon Launch System Exports, Aviation Week & Space Technology, pp. 28-29, April 20, 1987. The USA and the USSR have begun bilateral talks on this subject: Joint High-Level Declaration of US-Soviet Summit Meeting, Pravda/APN, 2 June 1988 (quoted after: Sowjetunion Heute, Dokumente vom Gipfeltreffen in Moskau, Sondernummer Juni 1988); USA und UdSSR: Export von Raketen begrenzen, Süddeutsche Zeitung, 29 September 1988.

25 Draft treaties banning anti-satellite weapons or space weapons in general have been published by private groups in the West, and by the Soviet Union officially: Union of Concerned Scientists et al., A treaty limiting anti-satellite weapons, Bulletin of the Atomic Scientists, no. 5, p. 10S, May 1984; Union of Soviet Socialist Republics, Draft Treaty on Banning the Use of Force in Space and From Space with Respect to Earth, Bulletin of the Atomic Scientists, no. 5, p. 11S, May 1984; H. Fischer, R. Labusch, E. Maus, J. Scheffran, Draft Treaty Limiting the Military Use of Space (in German), in: R. Labusch et al. (Eds.), Weltraum ohne Waffen, München: Bertelsmann, 1984, pp. 175-187 (for an English version, see: H. Fischer, The Military Use of Space and the International Legal System, in: J. Holdren, J. Rotblat (Eds.), Strategic Defences and the Future of the Arms Race, New York: St. Martin's, 1987, pp. 204-215).

26 The West German scientists' draft bans military command centers in space and direct guidance of nuclear weapons from space: Fischer et al. (note 25).

27 For a proposal how such limitations could be tailored to support a comprehensive ban on laser weapons, see: J. Altmann, Laser Weapons – Dangers for Strategic Stability and Possibilities of Preventive Arms Limitations (in German), Ch. 7, Marburg: Department of Physics, Philipps-Universität, February 1986.

Appendix

A-1 Program for Computing Ballistic Missile Trajectories

Ballistic missile trajectories are computed by numerical integration of the acceleration vector at discrete times t_i from launch to impact. At any discrete time point t_i, magnitudes and directions of the four force vectors (gravity, drag, lift, thrust) are computed according to (3-1) to (3-4) and the accompanying text. The mass of the K-stage missile at time 0 is

$$m_0 = m_p + \sum_{k=1}^{K} m_k, \tag{A-1}$$

where

$$m_k = m_{Rk} + m_{Fk}, \tag{A-2}$$

the mass of stage k, consists of housing etc. (m_{Rk}) and of fuel (m_{Fk}), and m_p is the payload mass. During burn of stage k, the total missile mass decreases linearly with time from ignition at t_{0k} to burnout at $t_{0k} + t_{Bk}$:

$$m(t_i) = m(t_{0k}) - \dot{m}_k\,(t_i - t_{0k}), \tag{A-3}$$

where

$$\dot{m}_k = m_{Fk} / t_{Bk}, \tag{A-4}$$

the mass exhaust rate of stage k, is constant over the burn time t_{Bk}. After burnout of each stage it is separated, and after a delay time t_{Dk} the next stage is ignited, starting with the mass

$$m(t_{0k+1}) = m_0 - \sum_{l=1}^{k} m_l. \tag{A-5}$$

After burnout of the last stage, the payload remains. Separation of a single warhead can be modeled by choosing the warhead mass, cross section area, and drag coefficient different from the respective payload values.

The local gravity acceleration at the altitude h is given by

$$g(h) = \mu / (R_E + h)^2, \tag{A-6}$$

here $\mu = 3.986 \cdot 10^{14}\ \mathrm{m}^3\,\mathrm{s}^{-2}$ is the product of Newton's constant and the earth mass and $R_E = 6.370$ Mm is the earth radius.

Atmospheric properties are modeled by the U.S. standard atmosphere;[1] Fig. A-1 shows the variation of air density ρ, mean molecular mass m_{mol}, and molecular scale temperature with geometric altitude. From these quantities, at each altitude h the temperature T_{mol} is gained from

$$T(h) = T_{mol}(h)\, m_{mol}(h) / m_{mol}(0), \tag{A-7}$$

and the velocity of sound follows from

$$v_S(h) = (\rho(h)\, R\, T(h) / m_{mol}(h))^{1/2} \tag{A-8}$$

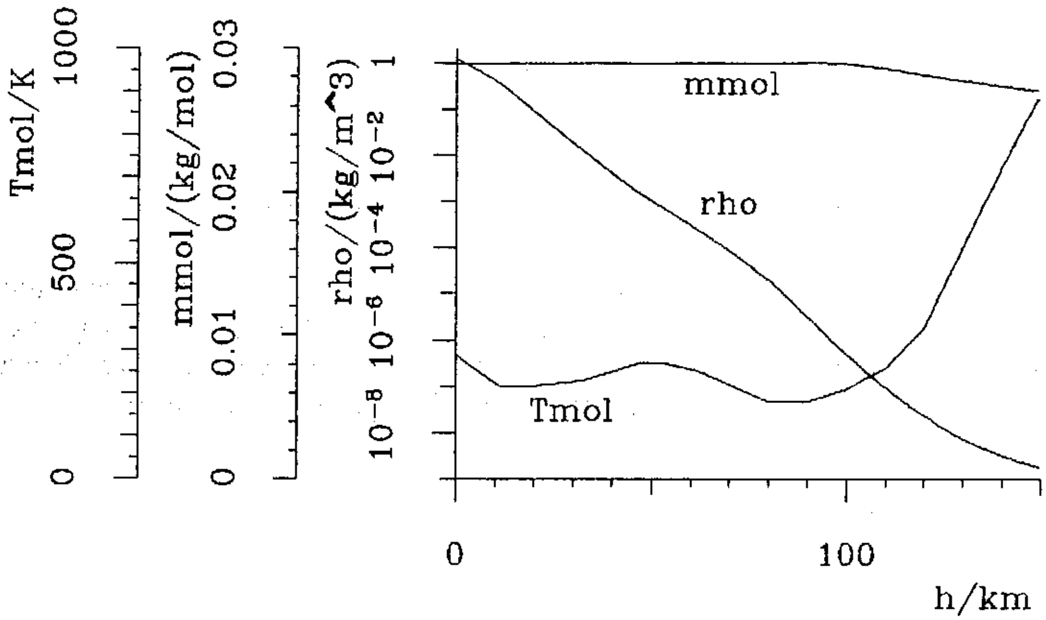

Fig. A-1 Variation of air density ρ, mean molecular mass m_{mol}, and molecular scale temperature T_{mol} with geometrical altitude h according to the U.S. standard atmosphere.

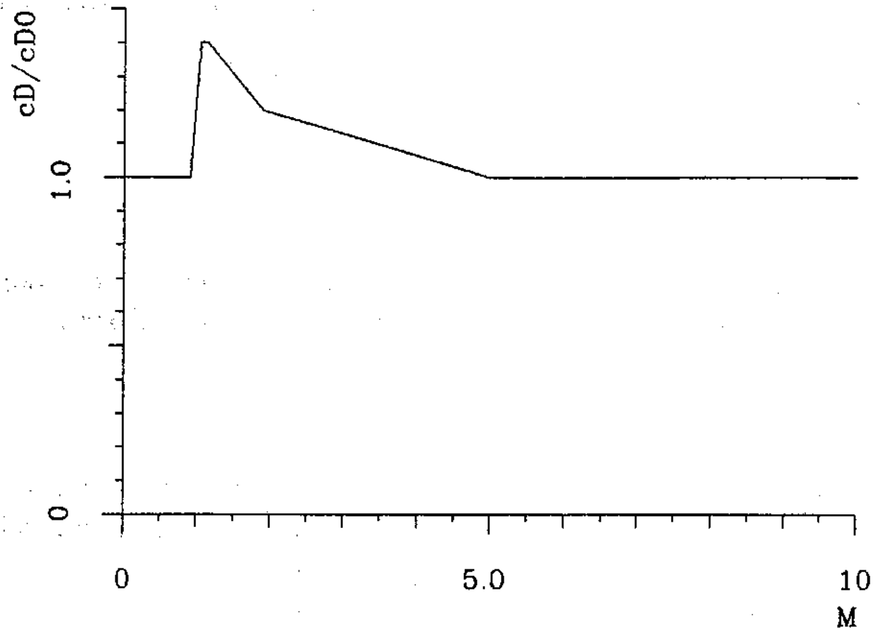

Fig. A-2 Model dependence of the relative drag coefficient c_D/c_{D0} on the Mach number M; the drag coefficient value at zero velocity, c_{D0}, is an input parameter; it is chosen as 0.25 for complete missiles, and 0.15 for reentry vehicles.

(R = 8.314 J/(mole·K) is the gas constant). This allows computation of the actual Mach number M from the actual velocity v:

$$M = v / v_S(h). \qquad \text{(A-9)}$$

The dependence of the drag coefficient c_D on the Mach number is modeled after a literature curve for the German V2 rocket at zero angle of attack;[2] its relative value is shown in Fig. A-2. The actual figure is gained by multiplying with the value c_{D0} at zero velocity; for complete missiles, c_{D0} is taken to be 0.25, for reentry vehicles, $c_{D0} = 0.15$. The dependence on the angle of attack is neglected (i.e., the angle of attack is supposed to be zero). During the boost phase, lift is not included in the computations (i.e., the lift force is zero). For vertical launch, lift is normally not used (except perhaps for course changes); for launch along constant elevation angles below 90°, inclusion of lift would result in minor corrections only. During reentry, for modeling of maneuvering reentry vehicles, sometimes a lift coefficient proportional to the drag coefficient is used:

$$c_L = c_1 \, c_D, \tag{A-10}$$

where $c_1 = +/-1$.

The thrust force of stage k is computed after

$$F_{Tk} = \dot{m}_k \, v_{ek} \tag{A-11}$$

(v_{ek} is the exhaust velocity of stage k), i.e. the nozzle exit pressure is assumed to match the surrounding air pressure at all altitudes. (When no motor is burning, this force is zero.) Its direction depends on the boost trajectory chosen. For ballistic missiles, a gravity turn trajectory is used; here the thrust force is antiparallel to the actual velocity vector at all times, and the velocity direction evolves by gravity during the boost time from near vertical to the burnout value required to achieve a certain range. For endoatmospheric interceptor missiles, the direction of the thrust force is changed from the negative velocity direction by an angle

$$\alpha = \arccos \left[\frac{F_G}{F_T} \cos\beta \sin\beta + \cos\beta \left(1 - \left(\frac{F_G}{F_T} \cos\beta\right)^2\right)^{1/2} - \beta \right] \tag{A-12}$$

(β is the desired trajectory elevation angle) in order to compensate for the gravity force. For exoatmospheric interceptor missiles, guidance is simulated by a vertical trajectory to 25 km altitude, after which a constant elevation trajectory is flown for the rest of the burn time. (In addition, for non-vertical launch the gravity force is compensated for as long as the missile is on its launcher, assumed to have a length of 20 m.)

The total force vector at any time is the sum of the individual forces:

$$\mathbf{F}(t_i) = \mathbf{F}_G(t_i) + \mathbf{F}_D(t_i) + \mathbf{F}_L(t_i) + \mathbf{F}_T(t_i). \tag{A-13}$$

Division by the actual mass $m(t_i)$ gives the acceleration vector at time t_i:

$$\mathbf{a}(t_i) = \mathbf{F}(t_i) / m(t_i). \tag{A-14}$$

Beginning at time $t_0 = 0$, the discrete times t_i at which trajectory variables are computed, are gained by adding a variable time interval Δt_i (see below):

$$t_i = t_{i-1} + \Delta t_i. \tag{A-15}$$

The velocity vector at time t_i is computed by time integration of the acceleration vector (according to the trapezoid method):

$$\mathbf{v}(t_i) = \mathbf{v}(t_{i-1}) + 0.5 \, (\mathbf{a}(t_i) + \mathbf{a}(t_{i-1})) \, \Delta t_i, \text{ with}$$

$$\mathbf{v}(0) = \mathbf{0}. \tag{A-16}$$

Similarly, the position vector derives from the velocity vector:

$$\mathbf{r}(t_i) = \mathbf{r}(t_{i-1}) + 0.5\,(\mathbf{v}(t_i) + \mathbf{v}(t_{i-1}))\,\Delta t_i, \text{ with}$$

$$\mathbf{r}(0) = (R_E, 0, 0). \tag{A-17}$$

(The coordinate system is centered at the earth center, the x axis pointing vertically upward at the launch point.)

In order to minimize discretization errors under conditions of fast changes, and to reduce computation effort and storage space, the integration time interval is determined dynamically according to the actual acceleration and the altitude; a preliminary value is defined by

$$\Delta t_{pi} = (10\ \text{m/s}) / a(t_{i-1}). \tag{A-18}$$

From this the final interval Δt_i is gained by multiplying by 10, if the missile is at altitudes greater than 80 km; then, the value is limited to lie between 1 ms and 10 s, and rounded to the next integer millisecond.

During flight, several quantities are monitored, and their maximum values are stored together with the times when they occurred. Other quantities are integrated over time. During the boost phase, this holds for: the maximum acceleration; the velocity losses due to gravity and to drag ((3-15) and (3-16)); the velocity, the elevation angle, the altitude, and the projected ground distance from the launch point at burnout. Over the whole trajectory, the maximum values of altitude and velocity are stored (with their time points). During reentry, the quantities stored are: the velocity, the ground distance, and the elevation angle at 80 km altitude; the maximum deceleration; the maximum heat power influx per area at the stagnation point according to (3-27), and its integrated energy per area; the maximum heat power influx into the reentry vehicle (3-23), and its integrated total energy having flowed into the vehicle.

For the thermal quantities of reentry, a skin friction coefficient of $c_F = 0.001$ is used. The wetted area of a cone-shaped reentry vehicle of base area A is taken as

$$S = A / \sin\varphi \tag{A-19}$$

with the half opening angle of the cone $\varphi = 10^\circ$.

During a trajectory run, all significant variables (acceleration, velocity, altitude, projected ground distance, heat power influx etc.) are stored at intervals given by the larger value of the two, the integration interval or a minimum time, usually 0.4 s. Afterwards, time courses of these variables, or the trajectory, can be plotted.

The program does not consider several features of real missile trajectories, inclusion of which would produce only minor corrections in the present context. These include: earth rotation; non-sphericity of the earth and other gravity anomalies; lift during the boost phase; moment balance on the missile; velocity components imparted to reentry vehicles by a post-boost vehicle; wind and other weather effects; different boost phase guidance schemes; thermal ablation during reentry.

Table A-1 gives the input parameters used for calculation of the trajectories of tactical ballistic missiles of different ranges, together with some derived quantities. For arriving at these values, the following procedure was used: Technical data of existing missiles of similar ranges were taken from the literature; for required data which were not available, estimates were made (e.g. for the partition of the masses of the different stages and of the payload, for the cross section areas etc.). Then, a set of values of mass distributions and exhaust velocities was iteratively arrived at, for which the maximum range attainable (i.e., at appropriate burnout elevation angle) was within one percent of the intended range. Burn times per stage are kept constant at 50 seconds, stage delay is 1 s in all cases. This procedure will not produce optimized missile designs; it is probable that real missiles have different properties. Because for the maximum range the velocity and direction at burnout are the most important parameters, however, variations will mainly affect the boost phase. In particular, it is possible that real missiles have shorter burn times and have one stage less at higher ranges. E.g., 500 km can be covered by one stage (as in the Soviet OTR-23, or SS-23, see Table 3-4). (If 5,000 km are to be covered by two stages (as in the Soviet RSD-10, or SS-20, the post-boost vehicle may act as a third stage.) The nose radius r_n (used for approximating the thermal power per area at the stagnation point) may be smaller for ranges below 5,000 km.

Table A-1 **Input data used in the computation of trajectories of ballistic missiles of different ranges. The theoretical burnout velocity v_{Bth} (excluding losses due to gravity and air drag) and the ballistic coefficient β of the warhead are derived quantities (eqs. (3-12) summed over the stages, and (3-18)); they are given for comparison purposes.**

Range, km	100	200	500		1,000		2,000		5,000			10,000		
No. Stages	1	1	2		2		2		3			3		
Stages:														
m_R, kg	100	200	450	370	450	370	490	340	2059	1190	282	1480	490	250
m_F, kg	235	570	2000	1270	2000	1270	3460	2160	14200	7160	2120	21190	7070	3530
v_e, km/s	2.55	2.55	2.07	2.07	2.55	2.75	2.35	2.75	2.3	2.6	2.7	2.5	2.7	2.7
t_B, s	50	50	50	50	50	50	50	50	50	50	50	50	50	50
t_D, s	1	1	1	1	1	1	1	1	1	1	1	1	1	1
A, m^2	0.126	0.283	0.785	0.385	0.785	0.385	0.785	0.785	3.14	1.43	0.48	2.21	2.21	1.37
c_{D0}	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Payload:														
m_p, kg	150	220	570		570		600		990			1200		
A, m^2	0.126	0.185	0.54		0.54		0.57		0.48			1.37		
c_{D0}	0.25	0.25	0.25		0.25		0.25		0.25			0.25		
Theoretical burnout velocity														
v_{Bth}, km/s	1.69	2.19	2.93		3.78		4.87		6.72			7.87		
Warhead:														
m_w, kg	150	220	570		570		600		280			330		
A, m^2	0.126	0.185	0.54		0.54		0.57		0.238			0.238		
c_{D0}	0.25	0.25	0.15		0.15		0.15		0.15			0.15		
β, Mg/m^2	4.76	4.76	7.04		7.04		7.02		7.84			9.24		
r_n, m	0.04	0.04	0.04		0.04		0.04		0.04			0.04		

A-2 Program for Computing Footprint Areas of Ground-Based Ballistic Missile Defense Systems

The general procedure for computing footprint areas, and the coordinate system used are described in 5.1.2. For a given interceptor missile, a set of trajectories of constant elevations during the boost phase is computed using the ballistic missile trajectory program of A-1, with elevation angles varying from 0 through 90° in 5° steps. For endoatmosperic interceptors, the constant elevation starts at launch. In order to model the near-vertical first phase of boost which is used with exoatmospheric interceptors in order to reduce the velocity losses due to air drag, their trajectories are taken to be vertical up to an altitude of 25 km. The rest of the boost phase is flown at the elevation chosen. The input parameters for the three interceptor types used here, are given in Table A-2. Trajectories are stored in the form of three linear arrays for time t, altitude h, and projected ground distance from the launch point s. From the set of 19 trajectories, a two-dimensional array $R(\beta_j, t_i)$ of possible interceptor distances R from the launch point zero is calculated by bilinear interpolation at common time points t_i along lines of constant elevation angle β_j (in s-h space) originating at zero. β values from 0 to 90° in 5° steps are used. This array is stored for any interceptor missile type, together with the linear array of the respective maximum numbers N_j of elements for any elevation β_j.

The trajectory of the ballistic missile or its reentry vehicle has also been stored in the form of linear arrays for time, altitude and projected ground distance from its launch point. This trajectory is transformed to the interceptor coordinate system in such a way that the impact point is at zero, and stored as a model. In the actual calculations, it is shifted horizontally in space to given impact points around the defense location, and in in time to fit into the defense-centered time scale.

A quantitative measure for the possibility of interception at a given impact point (r, Φ) in the horizontal (i.e., x-y) plane at a distance r from zero at an angle Φ with the x axis is determined in the following way: the actual trajectory of the reentry vehicle is gained by shifting the model trajectory in such a way that the impact occurs at (r, Φ). Then, by working backward in time, beginning at impact, the time when the reentry vehicle crosses the detection boundary is searched for (still in the model time frame). This is done by computing the difference

$$\Delta R_{Det}(t_{RV}) = R_{Det} - R_{RV}(t_{RV}) \qquad \text{(A-20)}$$

between the search detection range R_{Det} and the interpolated reentry vehicle distance from zero R_{RV} at suitable times t_{RV}, in the case of a given detection range. In the case of a detection altitude h_{Det}, the difference between this value and the reentry vehicle altitude h_{RV},

$$\Delta h_{Det}(t_{RV}) = h_{Det} - h_{RV}(t_{RV}) \qquad \text{(A-21)}$$

is used. As soon as a first negative value has been found, a zero approximation algorithm is started, and the detection time is found by the criterion that consecutive time points differ by less than 1 millisecond.[3] If the trajectory is completely inside the detection boundary, as can happen with short-range missiles, this shows up in all positive values of the difference. In this case the burnout time is taken as the detection time (motivated by the thought that only then tracking as a prerequisite for an interceptor launch decision can begin.) If the trajectory is completely outside the detection boundary (all difference values are negative), detection is impossible at all and no further computation occurs; the impact location is marked as being outside the footprint area by defining a negative value of the time margin (see below).

Detection time is time zero in the defense time frame, and the actual reentry vehicle trajectory is now shifted in time accordingly. In a way similar to the case of a detection altitude, the time t_{hminRV} is found when the reentry vehicle is at the given minimum interception altitude h_{min}, and the corresponding location is saved.

Interceptor launch is assumed to occur after a fixed delay time t_D. Between this time and the last time possible for sucessful intercept t_{hminRV}, a time is now searched for at which the reentry vehicle and an interceptor could meet at the same point in space. For a given time t, the reentry vehicle position is computed by interpolation of the stored actual trajectory, and the distance R_{RV} from zero is determined; then the elevation angle β leading to this point is computed. By bilinear interpolation of the stored array $R(\beta_j, t_i)$ at β and t, the distance R_{Int} is gained which a interceptor would have from zero, if it had been launched at t_D on a hypothetical trajectory leading to a position at the elevation β at time t. The difference between both distances,

$$\Delta R(t) = R_{RV}(t) - R_{Int}(t), \qquad \text{(A-22)}$$

is evaluated first at several test times t with $t_D \le t \le t_{hminRV}$, beginning at t_D. If a sign change to negative is found, a zero search is started. If all values are positive, the minimum is searched for to determine if the difference is positive on the whole interval.[4] If a sign change occurs, the first zero is determined, again using a 1 ms criterion, to be the time t_{IntRV} when intercept could have occurred. As a quantitative measure of the "ease of interception", the remaining time to the arrival of the reentry vehicle at the minimum intercept altitude is used. This time margin

$$t_m(r, \Phi) = t_{hminRV} - t_{IntRV} \qquad \text{(A-23)}$$

is positive, if interception is possible at altitudes above h_{min}.

If the difference $\Delta R(t)$ is positive at all times between t_D and t_{hminRV}, interception is impossible above h_{min} (or at all). In this case, the time margin is defined as

$$t_m(r, \Phi) = t_{hminRV} - t_{hminInt}, \qquad \text{(A-24)}$$

where $t_{hminInt}$ is defined as the time when an interceptor could arrive at the point where the reentry vehicle crosses the minimum altitude h_{min}. This time is gained by bilinearly interpolating $R(\beta_j, t_i)$ (for the elevation of that point in normal direction, and for the time from the distance in inverse direction). This $t_m(r, \Phi)$ value is negative. If the reentry vehicle is completely outside the volume accessible by interceptors, this is marked by defining a fixed negative $t_m(r, \Phi)$ value. If an interceptor position is needed at a time later than corresponds to the outermost point of the accessible volume at the elevation in question, the outermost distance value is taken as R_{Int}, and the interceptor is assumed to have been launched after an additional delay, after t_D, has passed.

This procedure is at first carried out at the defense location. If $t_m(0, \Phi)$ is positive, a whole footprint area is computed: along radii at azimuth angles Φ_l varying from 0 to 180° in 15° steps, impact positions are chosen with increasing distance values r, until $t_m(r, \Phi_l)$ becomes negative. Then the exact zero is searched for; because the time margin versus distance function often is not continuous at the footprint margin, here a sophisticated zero search algorithm is used too.[5] The search is stopped when consecutive distance values differ by less than 1 m. The footprint margin values $r_F(\Phi_l)$ are stored for later plotting etc.

For every program run, the following parameters are input: the mode of detection (altitude or range); the value of detection boundary R_{Det} or h_{Det}; the interceptor launch delay time t_D; the minimum interception altitude h_{min}; the azimuth angle increment for the footprint area, $\Delta\Phi$ (usually 15^o); the thresholds for finishing searches (usually 1 m in space and 1 ms in time); the direction of the ground projection of the reentry vehicle trajectory γ (here set to zero because of circular symmetry of the defense). Also input is the type of the interceptor (defining the array $R(\beta_j, t_i)$) and the type of the missile (defining the model trajectory).

For the trajectories of missile and interceptor, the coordinates are derived directly from the stored altitude h and projected ground distance s values (which are similar to cylindrical coordinates), without correction for the curvature of the earth. Distances R from zero are computed by

$$R = (x^2 + y^2 + z^2)^{1/2} \tag{A-25}$$

where (x, y, z) are the coordinates of the point in question. For smaller distances from the defense location (say, below 300 km), the deviation of the cartesian coordinates from the curved ones is negligible anyway. For larger distances, computation of both trajectories in s-h space results in implicit inclusion of the earth's curvature (the lines of "constant elevation" are curved in this case). Computing distances from zero by (A-25) leads to systematic deviations from the correct geometric distance; this does not influence the possible interception times t_{IntRV} because they are defined in a relative way, by the equality of the two distances R_{RV} and R_{Int}, the absolute values of which do not enter the calculation. Therefore, the time

Table A-2 Input parameters of the three different interceptor missile types used in the trajectory computation program. Type 1 is similar to a modified air defense missile like the U.S. Patriot; Type 2 is a high-acceleration, low-endoatmospheric interceptor similar to the U.S. FLAGE missile; Type 3 is a possible configuration for a missile carrying a light-weight exoatmospheric interceptor. Because for one-stage missiles no separation of the warhead occurs, the mass of the rocket housing etc. m_R has been set to a fictitious zero, its value being included in the payload mass m_P. The same holds for stage 3 of the Type 3 missile; stage 3 is the homing vehicle itself which uses part of its fuel for further acceleration in flight direction. The theoretical burnout velocity, a derived quantity, is given for comparison purposes.

	Type 1	Type 2	Type 3		
No. of stages	1	1	3		
Rocket mass m_R, kg	0	0	52	13	0
Fuel mass m_F, kg	640	80	468	117	4
Exhaust velocity v_e, km/s	2.45	2.8	2.6	2.8	2.8
Burn time t_B, s	12	2	15	15	10
Delay time t_D, s	0	0	0	0	0
Cross section A, m^2	0.132	0.042	0.292	0.159	0.031
Ref. drag coefficient c_{D0}	0.25	0.25	0.25	0.25	0.25
Payload:					
Mass, kg	270	150		36	
Cross section A, m^2	0.132	0.042		0.031	
Ref. drag coefficient c_{D0}	0.25	0.25		0.25	
Theoretical burnout velocity v_{Bth}, km/s	2.98	1.20		6.51	

margins t_m and the footprint margins r_F remain unchanged, too. The only effect not modeled here is the limitation of the search volume by the radar horizon for search ranges of 500 km and more. Because for search by airborne sensors the horizon is lower, and principles are to be demonstrated only, neglection of this effect is warranted.

A-3 Program for Computing Radiation Quantities

Properties of infrared sources and detectors are computed according to eqs. (4-15), (4-17), (4-19), (4-21) and (4-22). All spectral variables are defined on a linear grid of 400 wavelength values from 0 to 20 μm. Signal and background sources are defined as grey bodies, i.e. the blackbody spectral radiance at any wavelength λ,

$$L_\lambda(\lambda, T) = \frac{2\,h\,c^2}{\lambda^5}\,\frac{1}{e^{hc/(k\lambda T)} - 1}, \qquad \text{(A-26)}$$

(unit: $W/(m^3 ster)$) defined by a temperature T, is multiplied by a constant emissivity ε. (h: Planck's constant, c: velocity of light, k: Boltzmann's constant.) The sun is modeled by $T = 5{,}900$ K, $\varepsilon = 1$; the earth and its atmosphere by $T = 290$ K, $\varepsilon = 1$. Values of the emitted exitance M (unit: W/m^2) or power Φ are gained by appropriate multiplication with area and solid angle, and by numerical integration over the wavelength. No wavelength-dependent transmission through media is included. Geometrical beam expansion is included according to the distance r between the source and the optics. The optical system is defined by the area A_{Optics} and the focal length f. It can be supplied with a filter of constant transmission between two given wavelengths; the transmission loss is included in the overall optics loss F_L. A detector is defined by its quantum efficiency η (usually 0.5), its cutoff wavelength λ_c, the wavelengths λ_1 and λ_2 of a cooled filter, and the full opening angle 2Θ; with definition of the temperature T and the emissivity ε of the detector background, the maximum specific detectiviy $D^*(\lambda_c)$ is computed from (4-25); here the factor $F(2\Theta)$ is modeled after experimental values rather than using the theoretical $1/\sin\Theta$ dependence (Fig. A-3). The responsivity R is defined for a photovoltaic detector by

$$I = R\,\Phi, \qquad \text{(A-27)}$$

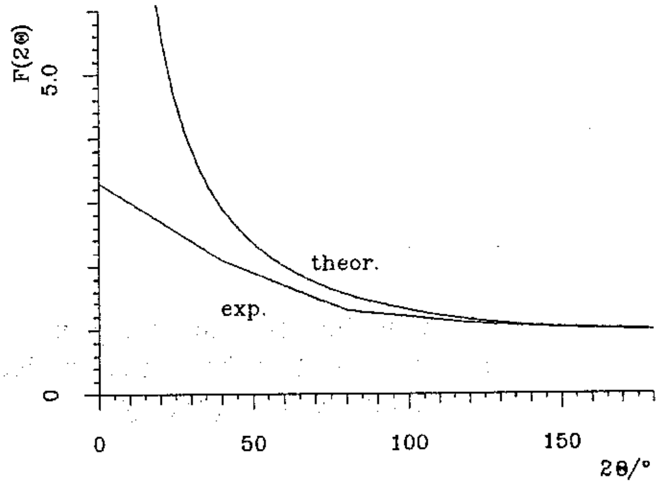

Fig. A-3 Dependence of the factor $F(2\Theta)$ used in the calculation of specific detectivity values, on the full opening angle 2Θ, after experimental results[6] (theoretical curve is shown too).

where the current I is produced by the radiation power Φ. Its maximum value is

$$R(\lambda_c) = \eta\, e\, \lambda_c / (h\, c). \qquad \text{(A-28)}$$

Both D* and R increase in proportion to the wavelength up to λ_c, and are zero above λ_c. Further detector characteristics are:

- the detector area A_D and the bandwidth B of the detection system; this allows calculation of the actual background noise power of the detector system after (4-24).
- the detector temperature T_D and its dark resistance R_D at zero bias voltage (photovoltaic detection is assumed); this allows to compute the diode saturation current

$$I_{sat} = k\, T / (e\, R_D). \qquad \text{(A-29)}$$

For background or signal, the power on the optics and the power on the detector are computed by integration over the wavelength, taking into account the correct wavelength-dependent quantities; e.g., the signal power on the optics which could in principle be sensed by the detector, is

$$\Phi_{OpticsS} = \int_0^{\lambda_c} A_S \frac{A_{Optics}}{4\, \pi\, r^2}\, L_{\lambda S}(\lambda)\, d\lambda \qquad \text{(A-30)}$$

(subscripts S denote the signal or source; A_S is the source area). The detector power is reduced proportionally, if in the case of an extended source the illuminated spot in the focal plane is larger than the detector area, or if under certain circumstances the diffraction image is larger than the detector. The background power on the detector is, e.g.,

$$\Phi_{DetBG} = \int_{A_{Det}} \left(\int_{\lambda 1}^{\lambda 2} A_{BG} \frac{A_{Optics}}{4\, \pi\, r^2} \frac{1}{F_L\, A_{spot}}\, L_{\lambda BG}(\lambda)\, d\lambda \right) dA. \qquad \text{(A-31)}$$

(In the case of an extended background its effective area A_{BG} is given by the projected area A_{FOV} of the field of view of the detector-optics system, (4-23).) Here, the area of the illuminated spot is either

$$A_{spot} = A_{BG}\, f^2 / r^2 \qquad \text{(A-32)}$$

as given by ray geometry, or

$$A_{spot} = (0.61 \pi \lambda)^2 / A_{Optics} \qquad \text{(A-33)}$$

as given by diffraction, whichever is greater.

Noise analysis is done in the following way: the signal and background photocurrents I_S and I_{BG} are computed by integration of the product of the respective detector spectral power density times the responsivity at the respective wavelength, e.g.:

$$I_{BG} = \int_{\lambda 1}^{\lambda 2} \Phi_{\lambda BG}(\lambda)\, R(\lambda)\, d\lambda, \qquad \text{(A-34)}$$

where $\Phi_{\lambda BG}(\lambda)$ is equal to the term under the inner integral of (A-31), integrated over the detector area. (For the signal current, exchange the subscripts appropriately.) The total detector shot noise current (for zero bias) is then given by [7]

$$I_{shot} = [\, 2\, e\, (I_S + I_{BG} + I_{sat})\, B\,]^{1/2} \tag{A-35}$$

(generation-recombination and 1/f noise is neglected).

For comparison purposes, the thermal noise produced in the feedback resistor R_f of the first current-to-voltage converting amplifier is computed using its temperature T_{Rf} from

$$I_{thermRf} = [\, 4\, k\, T_{Rf}\, B / R_f\,]^{1/2}. \tag{A-36}$$

The total system noise current can then be taken as

$$I_{noise} = [\, I_{shot}^2 + I_{thermRf}^2\,]^{1/2}, \tag{A-37}$$

and the system signal-to-noise ratio is computed from

$$S/N = I_S / I_{noise}. \tag{A-38}$$

(For the detector-related signal-to-noise ratio, the noise in the resistor would be excluded.)

Notes and References to the Appendix:

1 F. J. Regan, Re-Entry Vehicle Dynamics, New York: American Institute of Aeronautics and Astronautics, 1984, pp. 5-14.

2 G. P. Sutton, Rocket Propulsion Elements, New York etc.: Wiley, 1986, p. 100.

3 The Brent algorithm was used for the zero search, see: W. H. Press et al., Numerical Recipes – The Art of Scientific Computing, Cambridge etc.: Cambridge University Press, 1986, pp. 251-254.

4 The minimum search was done using the golden section algorithm, see: Press et al. (note 3), pp. 277-282.

5 Brent algorithm (note 3).

6 See Figs. 11-43 c and 11-51 c in: W. L. Wolfe, G. J. Zissis, The Infrared Handbook, Ann Arbor: Environmental Research Institute of Michigan, 1985.

7 D. Long, Photovoltaic and Photoconductive Infrared Detectors, Ch. 4, in: R. Keyes, Optical and Infrared Detectors, Berlin etc.: Springer, 1980.