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DEBRIS FROM BALLISTIC MISSILE DEFENCE: AN ANALYSIS TOOLS FOR POLICY/PLANNING STUDIES

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ORA PROJECT REPORT PR 688

DEBRIS FROM BALLISTIC MISSILE DEFENCE: AN ANALYSIS TOOL FOR POLICY/PLANNING STUDIES

by

Dr. Gregory W. Frank

MAY 1995

OTTAWA, CANADA

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Recommended By: Roger L. Roy, DAOR

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OTTAWA, CANADA

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ABSTRACT

Several Ballistic Missile Defence systems currently in development worldwide will rely on hit-to-kill interceptor technology to disable or destroy ballistic missiles and re-entry vehicles. Hit-to-kill interception at the very high speeds encountered in the missile regime will likely result in fragmentation of both the interceptor and the target missile. The fragments will then fall to Earth to form a debris field. This technology raises questions within the policy and strategy arenas. This Project Report describes the processes responsible for debris field formation. It also introduces a computer-based model which simulates the fragmentation process and the creation of a debris field. The model is intended as an analysis tool to support investigation for potential policy/planning questions, or to serve as a precursor to more detailed engineering studies.

RÉSUMÉ

Plusieurs systèmes de défense anti-missile en développement à travers le monde dépendent d'une technologie d'interception à impacte pour détruire des missiles balistiques ou des corps de rentrée. L'interception à impacte hypersonique résultera probablement à une fragmentation de l'intercepteur ainsi que du missile. Une étendue des débris est déduite par les points d'impacts sur la terre des différents fragments. On doit étudier cette technologie afin de répondre à des questions politiques et stratégiques. Ce rapport décrit le processus de formation de l'étendue des débris et présente un modèle informatique de simulation du processus de fragmentation et de la création de l'étendue des débris. Ce modèle sert d'outil d'analyse pour des questions politiques et stratégiques, ou peut être utiliser pour préconiser des études techniques plus détailées.

EXECUTIVE SUMMARY

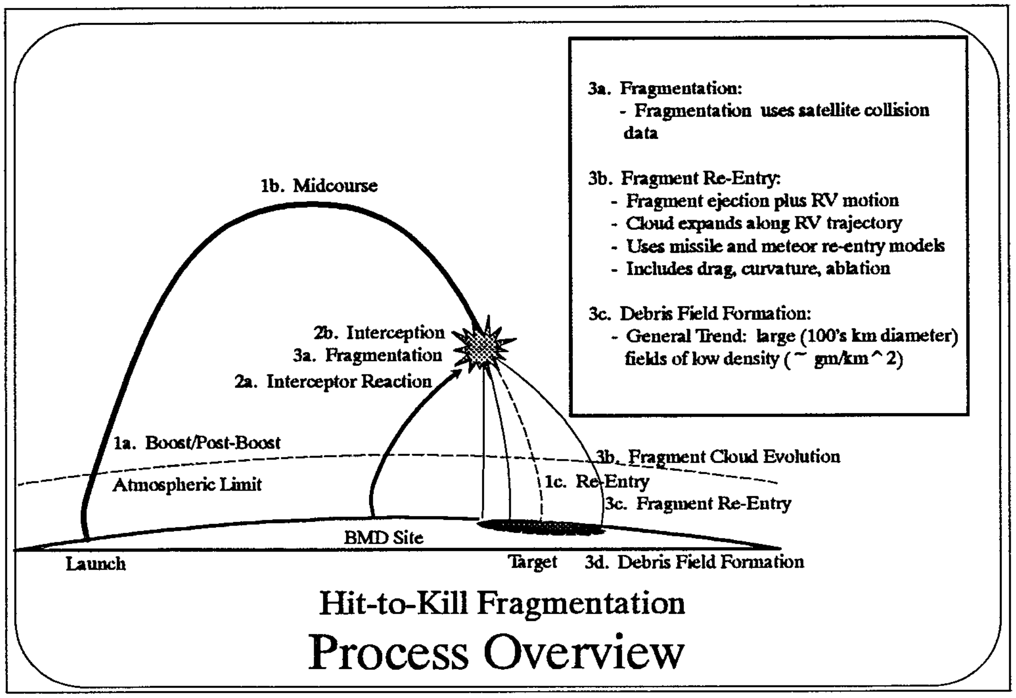
Ballistic Missile Defence (BMD) is a response to concerns about growing ballistic missile proliferation. Existing BMD systems such as Patriot are based on conventional air-defence systems adapted for a missile defence role. A number of systems currently being developed are being designed specifically for missile defence. These employ markedly different technologies. In particular, whereas the Patriot PAC-2 system used in the Gulf War used a proximity fuzed blast fragmentation warhead, systems such as the PAC-3 upgrade and THAAD Theatre Missile Defence systems will use direct impact hit-to-kill interceptors. The use of this technology changes the basic capabilities of missile defence and may raise questions within the policy and strategy arenas.

With hit-to-kill technology, a small and fast Kinetic Kill Vehicle is used to collide with a ballistic missile or Re-entry Vehicle (RV). The energy accompanying a body-to-body impact at speeds of several kilometres per second is adequate to ensure RV destruction. Laboratory and range tests have indicated that the RV is likely to be fragmented into many small pieces. These pieces are hurled away from the interception site at high speed by the energy of the collision. This raises questions in a policy or strategy venue. For example, given a successful interception, how many small or large fragments are likely to be produced, and where are they likely to land? What risk hazard is associated with falling debris? Can these hazards be managed by controlling the intercept location?

This Project Report documents work done in the Directorate of Air Operational Research, as part of a project to develop analytical tools to examine issues in BMD in support of potential policy studies. The tools are designed to assess the ability of a missile defence system to defend an extended area, and the consequences of that defence. This report documents an analytical tool developed to assess some of the consequences of BMD. It describes a computer-based package which simulates the probable strewn debris pattern resulting from a high velocity missile/interceptor collision. The model serves as a 'first-order' assessment tool, modelling processes with sufficient detail to illustrate the central issues. It can either serve to augment policy or strategy studies, or as a precursor to more detailed engineering or systems-level simulations.

This Project Report is a non-technical description of the model and its capabilities. Technical documentation is provided in an accompanying Research Note. While this study does not address specific intercept scenarios, several trends have emerged which deserve comment. Interceptions of long-range Ballistic Missiles using a National Missile Defence scenario can occur hundreds of seconds before scheduled warhead impact. These are usually characterized by large debris fields several hundreds of kilometres in diameter. Assuming a constant fragment distribution gives fragment densities on the order of a few grams per square kilometre. While the exact size and shape of the fragment field is sensitively dependent upon the intercept conditions, such low densities are typical of long-

range intercepts. The processes responsible for debris field formation are summarized in the following figure.



The following recommendations are made for the use of this analysis tool:

a. an examination of the relative risk posed by debris from current lower-tier TMD systems used in peacekeeping or global contingency scenarios;

b. an examination of the relative risk posed by debris from proposed TMD systems in peacekeeping or global contingency scenarios, using TMD systems such as Patriot, THAAD and Boost-Phase Intercept systems; and

c. use of the model in support of scientific studies of kinetic energy lethality mechanisms.

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LIST OF ABBREVIATIONS

ABM	Anti-Ballistic Missile
BMD	Ballistic Missile Defence
DAOR	Directorate of Air Operational Research
DGOR	Director General Operational Research
EAD	Extended Air Defence
E^2I	Exoatmospheric/Endoatmospheric Interceptor
FY	Fiscal Year
gm	Gram
GBI	Ground-Based Interceptor
ICBM	Inter-Continental Ballistic Missile
IR	Infrared
IV	Interception Vehicle
kg	Kilogram
KKV	Kinetic Kill Vehicle
km	Kilometre
LEAP	Lightweight Exoatmospheric Projectile
m	Metre
NMD	National ballistic Missile Defence
RV	Re-entry Vehicle
TBM	Theatre (Tactical) Ballistic Missile
THAAD	Theatre High Altitude Area Defence
TMD	Theatre ballistic Missile Defence

DEBRIS FROM BALLISTIC MISSILE DEFENCE: AN ANALYSIS TOOL FOR POLICY/PLANNING STUDIES

I. INTRODUCTION

PROJECT BACKGROUND

1. Worldwide ballistic missile proliferation has prompted several nations to consider Ballistic Missile Defence (BMD) systems for national and theatre defence. Currently, the United States is developing several systems for Theatre Missile Defence/Extended Air Defence (TMD/EAD), which will lead to technologies for National ballistic Missile Defence (NMD). The majority of these systems employ hit-to-kill interceptor technology, in which a threat missile is disabled or destroyed through physical collision with an Interceptor Vehicle (IV). At the extremely high velocities encountered in the missile regime, the energy of this collision is often sufficient to disintegrate the threat missile into small fragments. The fragments then fall to Earth to form a debris field.

2. This process raises a number of questions within policy and strategy venues. In the case of TMD, intercepts may occur during missile re-entry: would fragments from the interception of a missile carrying a high-energy explosive warhead cause more or less collateral damage than an unintercepted warhead? Would interception of a chemical or biological warhead facilitate contaminant dispersal? Within a NMD context, interceptions would take place during missile midcourse at altitudes of hundreds of kilometres, possibly over Canadian territory (Reference 1). Where would this debris land? What is the relative risk posed by falling debris, in comparison to an unintercepted warhead? Can intercepts be tailored to control the debris field?

3. This Project Report describes a computer model which addresses these questions by simulating the formation of strewn debris fields from a hit-to-kill BMD system. The model operates at a level of fidelity sufficient to demonstrate the central issues of field formation without obscuring the major results beneath layers of technical detail. This

report provides a non-technical description of the interception and fragmentation processes and their modelling. Technical details are available in a companion document (Reference 2).

4. This work was done in the Directorate of Air Operational Research (DAOR) as part of DGOR Activity 23213 (Analysis of Space-Related and Space-Systems). A series of projects under this activity has developed a set of computer-based models on space-based and space-related defence systems, including:

a. Theatre and Intercontinental Ballistic Missile (TBM and ICBM respectively) trajectory simulations (Reference 3);
b. Ballistic Missile interception models (Reference 4); and
c. Ballistic Missile Defence (BMD) simulations (Reference 1).

These projects have been accompanied by a survey identifying areas of possible interest from the policy and planning perspective (Reference 5). The goal of the modelling work is twofold: to examine the ability of a BMD system to defend an extended area, and to determine the consequences of that defence.

5. To establish a context for the following work, it is useful to summarize the path being taken by the U.S. BMD programme. As a result of the U.S. Department of Defense Bottom-Up Review, the Fiscal Year (FY) 1995 President's budget, the Missile Defence Act (amended) and the FY 1995 Authorization and Appropriation Bills, top priority is given to the development of a Theatre Missile Defence Capability. Second priority is the implementation of a National Missile Defence. Third priority is advanced follow-on technologies. The work conducted by the Ballistic Missile Defence Organization (BMDO) will remain within the constraints of the 1972 ABM Treaty (Reference 6).

AIM

6. This paper describes, in non-technical terms, the formation of the debris field resulting from hit-to-kill Ballistic Missile Defence technology. A computer-based assessment tool which simulates the field creation process is introduced.

SCOPE

7. This paper demonstrates the use of an analysis tool in support of policy and strategy studies concerning Ballistic Missile Defence. It is a non-technical description of the major physical processes occurring during ballistic missile interception. A technical description is available as a companion document (Reference 2).

II. METHOD

8. This section describes the basic processes at work in the creation of a debris field. The discussion is non-technical, and intended to convey the nature of the processes and their modelling. Following a description of ballistic missile flight, Ballistic Missile Defence systems, and hit-to-kill interception, the processes responsible for debris field creation are described in terms of a reference scenario.

PHASES OF BALLISTIC MISSILE FLIGHT

9. Ballistic Missile Defence involves events occuring at speeds and over time scales outside most everyday human experience. Table I establishes a context for the missile performance regime. Representative time, length and velocity scales are indicated for each major phase of missile flight for both Theatre and Intercontinental Ballistic Missiles. Ballistic Missile flight consists of three major phases:

a. *Boost phase:* from missile launch to main thrust burnout. A *post-boost phase,* in which Re-entry Vehicles (RVs) are targetted and deployed, may also occur.

b. *Midcourse phase:* the unpowered flight phase from thrust burnout to atmospheric re-entry. The missile or RV is in freefall during this phase, and behaves as a satellite in an Earth-crossing orbit.

c. *Re-entry phase:* from atmospheric re-entry at an altitude of approximately 100 km to impact or warhead detonation. This phase is characterized by the missile or RV being rapidly slowed by the Earth's atmosphere, causing the warhead to experience intense heat and stresses.

Missile Defence systems can be designed to operate during any phase of ballistic missile flight, and each phase has its own advantages and poses its own special problems. This paper is concerned primarily with defence systems operating in the midcourse and re-entry phases of missile flight.

TABLE I
PHASES OF BALLISTIC MISSILE FLIGHT[1]

Missile Range	Boost	Midcourse	Re-Entry
TBM (600 km)	90 sec, 50 km alt, 1 km/sec.	250 sec, 150 km alt, 2 km/sec.	60 sec, 100 km alt, 1.5 km/sec.
ICBM (10,000 km)	300 sec, 200 km alt, 3.5 km/sec	1000 sec, 1000 km alt 7 km/sec	20 sec, 100 km alt, 5 km/sec

COMPONENTS OF A BALLISTIC MISSILE DEFENCE SYSTEM

10. A Ballistic Missile Defence system consists of early warning sensors, battlespace surveillance and management sensors, and interceptor systems. These components carry out the major functions of a BMD systems: target acquisition, tracking, discrimination, interceptor control and target kill (Reference 7). The class of BMD systems of primary interest here consist of a central radar sensor managing the battlespace surrounding the BMD system. Peripheral early warning assets provide ballistic missile detection and serve to cue the BMD radar sensor. The BMD radar performs tracking, discrimination and interceptor flyout control, and also provides the highly accurate track information to perform discrimination and to select potential intercept points. The RV has limited maneuverability during midcourse, and its trajectory is highly predictable. The interception process is more akin to a satellite rendezvous, rather than an air defence intercept in which the target aircraft can actively avoid the interceptor.

HIT-TO-KILL INTERCEPTION

11. Current emphasis is being placed on missile defence by hit-to-kill interception. Hit-to-kill interceptors are conceptually appealing for one basic reason: they turn the

[1] Source: Weiner (Reference 7).

primary advantage of ballistic missiles against themselves. Ballistic missiles cover large distances at very high speeds: hit-to-kill interceptors use this high speed to destroy the missile. The energy of motion of a moving body is called *kinetic energy:* kinetic energy increases with the mass and speed of a body.[2] At the speeds encountered in the Ballistic Missile regime, even a small mass of a few kilograms can be a very effective interceptor. Hit-to-kill interceptors, or Kinetic Kill Vehicles (KKVs), consist of lightweight Interceptor Vehicles launched atop multi-stage anti-ballistic missiles. Dependent upon the Ballistic Missile Defence system configuration and ballistic missile flight profile, TMD and NMD intercepts will occur during missile midcourse or re-entry at altitudes of tens to several hundreds of kilometres, respectively. The Interception Vehicle proper consists of sensors, guidance and navigation modules combined into a package weighing a few tens of kilograms (Reference 8).

12. The Interceptor Vehicle flyout is controlled by the BMD radar. In the interceptor systems of interest here, the terminal engagement is guided by radar or infrared sensors, located on-board the interceptor. Targeting information is passed from the BMD sensor to the interceptor as a Target Object Map, indicating the target from the background field of decoys and accompanying missile debris. The following paragraphs summarize several Ballistic Missile Defence systems employing hit-to-kill technology that are in the planning or development stage.

Patriot Anti-TBM Capability Upgrade 3 (PAC-3)

13. The Patriot air defence system was originally designed as a surface-to-air missile to operate against saturation aircraft raids. Modifications to engage TBMs were proposed

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2 Kinetic energy increases linearly with the mass of a body, but increases as the *square* of its speed. Therefore, doubling the mass of an interceptor doubles the kinetic energy, but doubling the speed of the interceptor *quadruples* the kinetic energy available for warhead destruction. The kinetic energy associated with the speeds encountered in the missile regime is enormous: even at the relatively slow speeds of Theatre Missile Defence (about 2 km/sec for both missile and interceptor), a head-on collision with an interceptor carries the destructive energy as the same weight of high-energy explosives.

in the late 1970s in response to increasingly accurate Soviet Scud missiles. The initial Patriot Anti-TBM Capability upgrade (PAC-1) began in 1984, and involved modifications to the radar search and track algorithms, and a larger radar scan volume. PAC-2 modifications included further algorithm refinements and improved interceptor fuzing and warhead construction for the TBM threat. PAC-2 was flight tested in 1987 and used against Iraqi missiles in the 1991 Gulf War. Currently, a PAC-3 upgrade programme has been initiated. This includes radar enhancement, remote launch, communications upgrades and a hybrid hit-to-kill/fragmentation active radar missile based on the Exoatmospheric Re-entry Interceptor (ERINT) (Reference 9). PAC-3 is designed as a lower tier system providing late midcourse and re-entry interception with a coverage radius of several tens of kilometres against TBMs with ranges up to 1,000 km (Reference 10).

Theatre High Altitude Area Defence (THAAD)

14. THAAD is an upper tier system. It consists of a Ground-Based TMD Radar designed to provide a large TMD battlespace. It uses a passive infrared-guided Interceptor Vehicle carrying a 35 kg Kinetic Kill Vehicle. It will engage at long ranges and high altitudes to provide the capability of multiple engagements. THAAD will provide a coverage radius of several hundred kilometres against TBMs with ranges up to 2,000 km. THAAD is currently in the Demonstration/Validation process, with Engineering and Manufacturing Development scheduled for 1997 (Reference 11).

Aegis Weapon System Standard Mark 2 Block IVa Modification

15. This system exploits the unique opportunities available with a ship-based TMD system. By positioning the TMD system close to the missile launch site, a wider range of threat trajectories can be intercepted. This results in a larger defended area. Currently envisioned as a long-range upper tier capability, candidates for this naval TMD capability include interceptors based on the THAAD missile, or a Standard Mark-2 Block IV missile boosting a Lightweight Exoatmospheric Projectile (LEAP) (Reference 10).

National Missile Defence (NMD) System

16. Under the 1991 Missile Defence Act, the U.S. Congress has directed that a National Missile Defence capability be developed to defend the continental United States against Intercontinental Ballistic Missile attack. NMD is currently viewed as a long-term requirement growing out of TMD technology developments. Current NMD plans call for early warning to be provided by space-based assets and the Ballistic Missile Early Warning System (BMEWS). The NMD site, located at Cavalier, North Dakota, is to use a Ground-Based Radar based on the Perimeter Acquisition Radar Attack Characterization System (PARCS). This provides a battlespace of several thousand kilometres radius. NMD interceptors such as the Endo-Exoatmospheric Interceptor (E^2I) will be based on technology from THAAD and related systems. They will provide a defended area of several thousand kilometres radius against ICBMs (Reference 12).

17. Table II summarizes Interceptor Vehicle performance characteristics of some representative systems.

TABLE II
REPRESENTATIVE HIT-TO-KILL INTERCEPTOR CHARACTERISTICS

SYSTEM	ENGAGEMENT RANGE/ALT	SIZE	INTERCEPTOR
PAC-3 (ERINT)	<15 km ~20 km range ~1.5 km/sec flyout	4.6m / 0.34m 305 kg launch	- active radar seeker - KKV & tungsten pellet fragments
THAAD	15-100 km, ~150 km range, ~2.0 km/sec flyout	5.0m/0.5m 1,000 kg launch	- IR seeker -35 kg KKV
E^2I[3]	100-1,000 km alt, ~5,000 km range, ~6.5 km/sec flyout	6.5 m/ 0.49 m 1,200 kg launch	- IR seeker - 10-20 kg KKV

[3] The Exoatmospheric-Endoatmospheric Interceptor (E^2I) is one of a number of interceptor design alternatives for a National Missile Defence system (Reference 8,12).

REFERENCE SCENARIO

18. To illustrate the processes at work in forming strewn fields, consider the following hypothetical intercept scenario. Assume an Intercontinental Ballistic Missile (Re-entry Vehicle mass 1000 kg, speed at intercept 5 km/sec) is intercepted using a continental BMD system (Interceptor Vehicle mass 10 kg, speed 5 km/sec). Assume that Early Warning sensors have allowed the Interception Vehicle to be launched early enough to intercept the Re-entry Vehicle at an altitude of several hundred kilometres, outside the Earth's atmosphere (exoatmospherically). Figure 1 shows the principal events in missile interception and subsequent debris field production.

PROCESS OVERVIEW

19. The debris field creation process is composed of three distinct sub-processes:

a. Re-entry Vehicle interception and fragmentation;
b fragment re-entry; and
c. fragment ground impact and debris field creation.

This section is a non-technical description of these processes. The principal events following Re-entry Vehicle destruction by a hit-to-kill interceptor are described, and their inclusion into a computer-based model outlined. This section is explanatory only: for technical details please refer to the companion document (Reference 2).

PROCESS A: RE-ENTRY VEHICLE INTERCEPTION AND FRAGMENTATION

20. Assume for simplicity that interception occurs head-on, with the interceptor striking the Re-entry Vehicle at a relative speed of 10 km/sec. Part of the energy of the collision goes into fragmentation: tests indicate about half the available kinetic energy is used for fragment creation and dispersion. While relatively little is known about materials properties under the extreme stresses experienced during extremely high speed collisions, enough data has been collected through laboratory and range tests to establish a basic understanding of the fragmentation process.

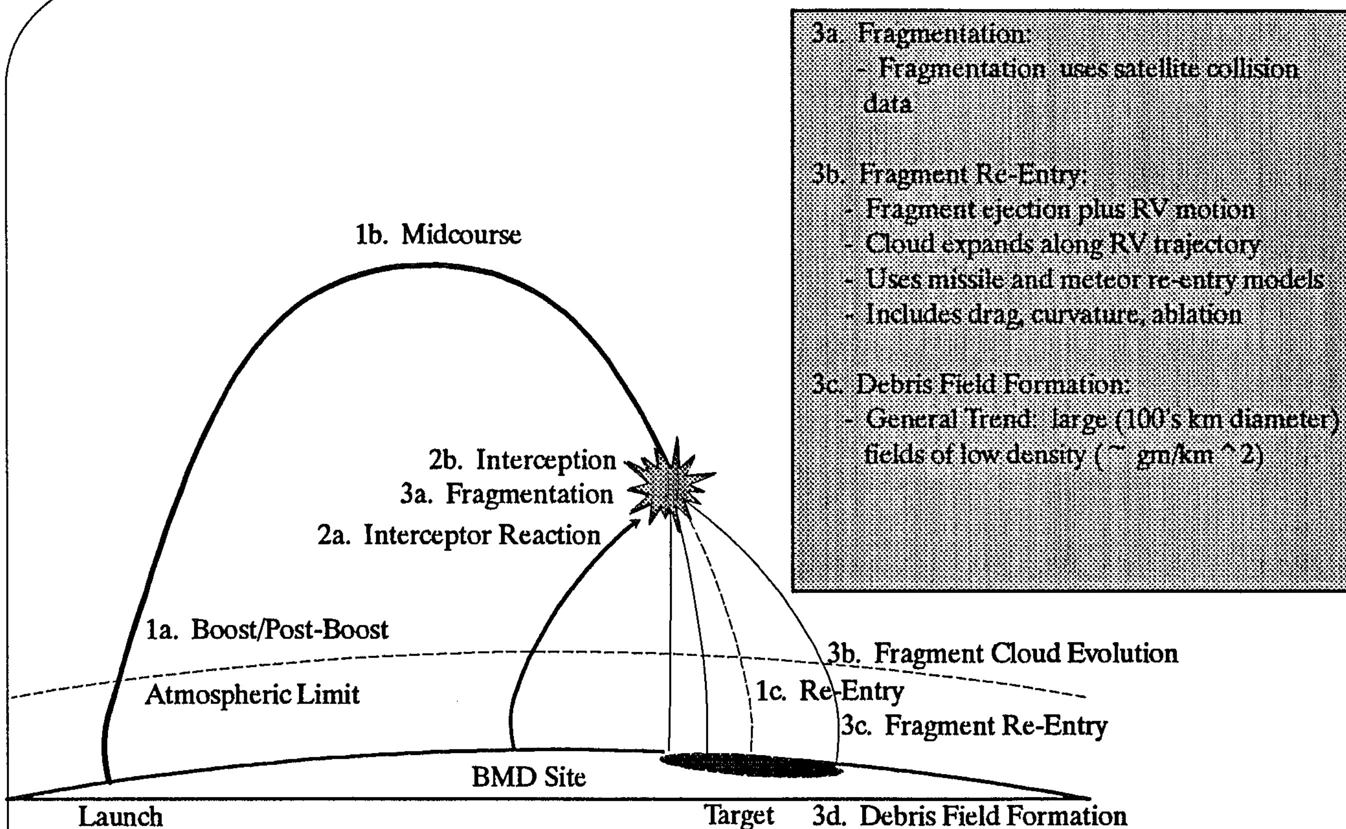

Figure 1: Hit-to-Kill Fragmentation

Process Overview

21. Figure 2 shows part of a database of laboratory and range test results. The figure, taken from Reference 2, shows the greatest expected fragment ejection speed as a function of fragment mass for several intercept speeds. Lighter fragment masses are more easily accelerated by the collisional shock wave, and so are ejected with higher average speed, on the order of several kilometres per second for most intercepts. Larger and heavier fragments, weighing on the order of kilograms, are ejected at slower velocities, on the order of tens of metres per second. Small fragments can be ejected with very high speeds. A Theatre Ballistic Missile interception occurring at a relative speed of about 5 km/sec results in small fragments being ejected at speeds as high as 7 km/sec. This is on the order of the orbital speed of a low-Earth orbiting satellite.

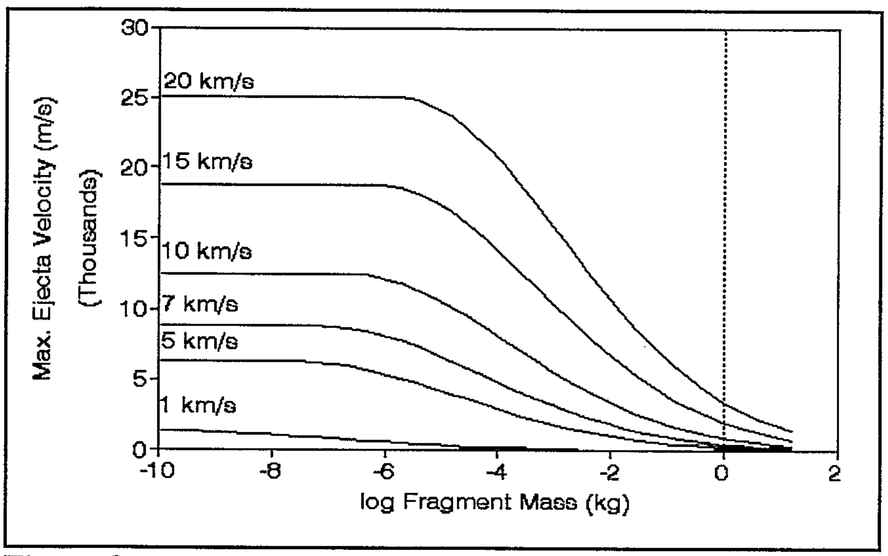

Figure 2 Representative Fragment Velocity Distribution

22. The available literature on hypervelocity collisions indicates that interception produces many small fragments. At the speeds encountered in the NMD regime, the energy of the collision is sufficient to result in almost complete fragmentation of both the Re-entry and Intercept Vehicles. Relatively few fragments survive with a mass more than

a few grams. Within the TMD regime, lower interception speeds result in less energy available for fragmentation. Fragments are larger and are ejected at a lower speed than in the NMD regime.

PROCESS B: FRAGMENT RE-ENTRY

23. Following interception, the fragments form a debris cloud. The evolution of the debris cloud can be understood by considering the behaviour of its constituent fragments. In a midcourse interception, the collision occurs outside the Earth's atmosphere in a near-perfect vacuum. The ejected fragments follow their own ballistic trajectories until they reach the upper atmosphere at an altitude of about 100 km.

24. The nature of each fragment's trajectory is determined by its position and momentum at the instant of intercept. This can be modelled by considering the momentum of the Re-entry Vehicle at the instant of collision.[4] At that instant, each fragment is still a part of the Re-entry Vehicle body. In the demonstration scenario, each fragment is moving forward with a speed of 5 km/sec with respect to the Earth's surface. After the interception, the fragment is hurled away with an ejection velocity superimposed over the Re-entry Vehicle's original forward motion. The net effect is that each fragment is ejected with a component of motion along the original Re-entry Vehicle trajectory.

25. Combining the trajectories of several fragments allows the evolution of the debris cloud to be modelled. The cloud continues to travel along the original trajectory of the

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[4] Each fragment's behaviour can be understood as a consequence of the Law of Conservation of Momentum. Momentum is defined as the product of a body's mass and its velocity. For example, in the demonstration scenario the momentum of the Re-entry Vehicle is 1000kg x 5 km/sec = 5×10^6 kg m/sec. The Law of Conservation of Momentum states that, under relatively general conditions, the total momentum of two bodies before collision is equal to the momentum of the system after collision. In this context, the sum of momentum of the Re-entry and Interceptor Vehicles before collision is equal to the sum of momentum of all fragments after collision. That is, the fragments are ejected symmetrically in all directions with respect to the Re-entry Vehicle. With respect to an observer on the Earth's surface, fragments are ejected with a velocity component along the Re-entry Vehicle's original direction of motion.

Re-entry Vehicle. As time passes, the cloud spreads out to form a large diffuse 'halo' of very light fragments surrounding a core formed of a few heavier fragments. The cloud continues to spread uniformly about the original trajectory until it reaches the Earth's atmosphere at an altitude of about 100 km. The atmosphere at this altitude is sufficiently dense to begin decelerating lighter fragments. Heavier fragments are decelerated later in the denser atmosphere encountered at lower altitudes. Fragment behaviour during re-entry is modelled using the same equations of motion governing ballistic missile and spacecraft re-entry.[5]

26. Figure 3 shows the result of a calibration test performed upon the computer model. In the figure, a 1000 kg Re-entry Vehicle is travelling horizontally at 5 km/sec towards the right of the page. A 10 kg Interceptor Vehicle is travelling horizontally at 5 km/sec towards the left of the page. The interception is assumed to occur at 20 km altitude. This is a low intercept altitude, but one which demonstrates the role of the Earth's atmosphere in slowing fragments. The figure shows the trajectories of 100 gm fragments. From Figure 2, these are ejected at a speed of about 3 km/sec with respect to the Re-entry Vehicle. That is, with a range of speeds from 2-8 km/sec with respect to a ground-based observer. The 100-gm fragments are decelerated by the Earth's atmosphere, and land over a range of distances up to about 85 km downrange of the intercept location.

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[5] Fragment motion during re-entry is determined by considering the forces due to gravity and the atmosphere acting at each step of the fragment's trajectory. The atmosphere model used describes the atmosphere's variation in density with altitude. The possibility of fragment mass loss due to atmospheric friction is considered by incorporating a mass loss model from meteor re-entry physics.

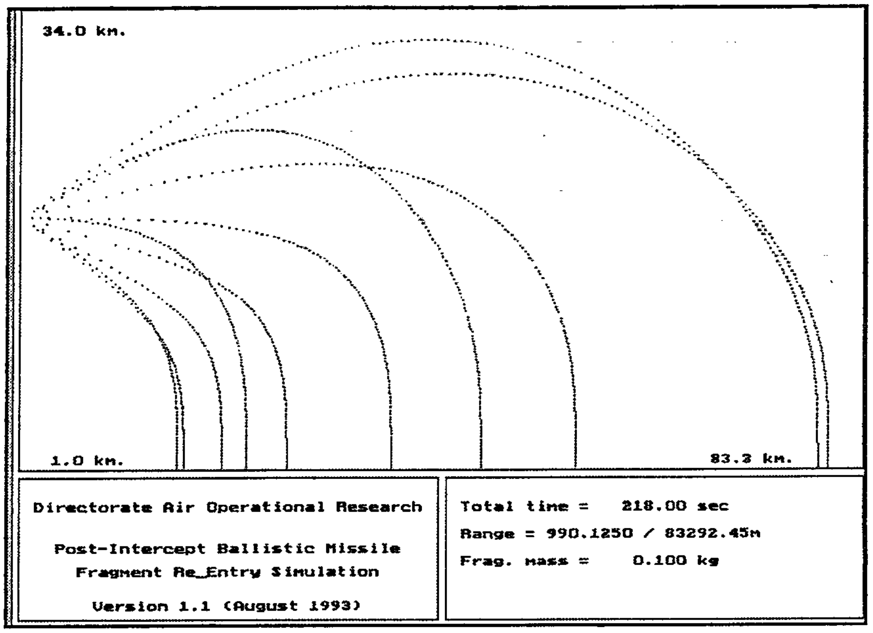

Figure 3: Fragment Re-Entry Trajectories

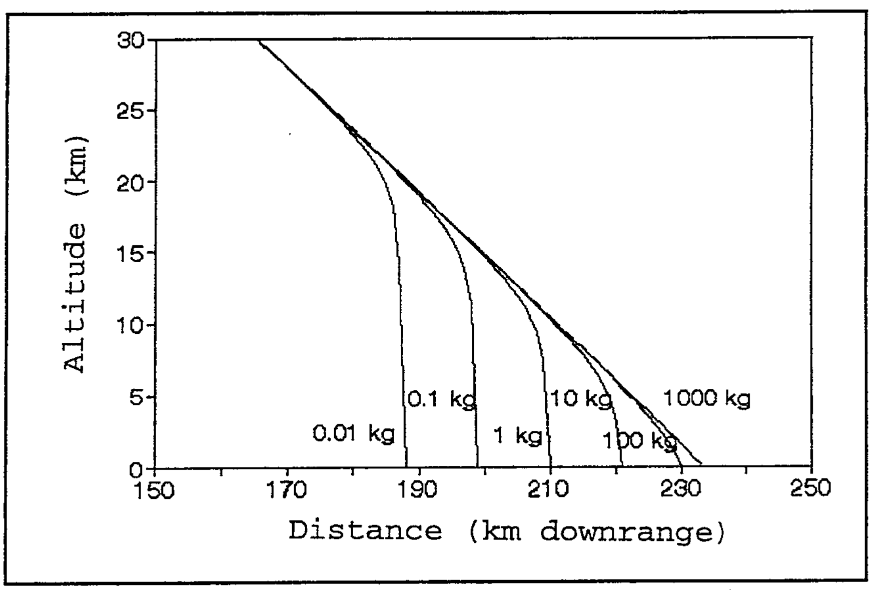

Figure 4: Demonstration Fragment Re-entry Trajectories.

PROCESS C: GROUND IMPACT AND DEBRIS FIELD CREATION

27. Figure 4 shows the results of a calibration run of the re-entry model. Bodies with masses ranging from 10 gm to 1,000 kg re-enter the Earth's atmosphere with identical initial velocities of 5 km/sec directed at 22.5° to the horizon. The trajectories of very heavy fragments (for example the 1,000 kg body, representing an unfragmented Re-entry Vehicle) are almost completed unaffected by the Earth's atmosphere over the length scales shown. In contrast, lighter fragments are slowed by atmospheric drag. Less massive fragments are more efficiently decelerated and strike the Earth's surface further uprange. The debris field thus produced has a complicated structure. Fragments of different masses distributed in a complex manner dependent upon the missile's position and velocity at intercept.

28. The debris cloud is modelled by simulating several fragments with a range of masses. Typically, a set of 64 masses are modelled, 16 fragments in each of four different mass classes. Their trajectories are computed, and their impact points stored. These are used to estimate the probable extent of the strewn debris field resulting from either single or multiple interceptions. Figure 5 shows the debris field resulting from a typical intercept. The projectile's impact point in the absence of interception is denoted by the '**X**'. The figure shows four superimposed off-centre circles: each circle corresponds to one set of fragments of constant mass. The field of Figure 5 results from a calibration scenario similar to the one which generated Figure 4: a low-altitude collision in which both vehicles were travelling horizontally. The total momentum in this case is directed towards the left of the page. The largest circle denotes the extent of the debris field formed by the lightest fragments, in this case 100 gm. These fragments are ejected with the highest speed, but are also the most quickly decelerated by the Earth's atmosphere. The smallest circle to the left of the page is the field component formed from the heaviest fragments (100 kg). These fragments have the lowest ejection speed, but are the least affected by the Earth's atmosphere, and land furthest downrange from the intercept point.

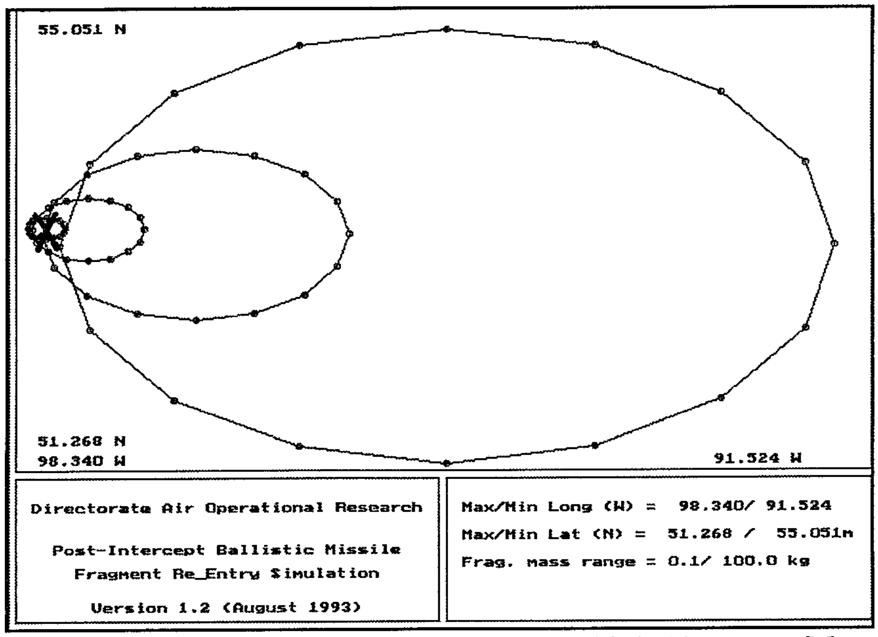

Figure 5: Demonstration Debris Field: Multiple Fragment Mass Contours

III. DISCUSSION

29. This section presents some of the trends observed during the modelling process, and identifies possible avenues for continued activity. It is divided into three parts: the first presents general considerations of Ballistic Missile Defence and interception related to the scope of this paper. This is followed by trends observed during the modelling process, and concludes with a short paragraph suggesting further avenues of research.

30. A recent Ballistic Missile Defence Organization (BMDO) briefing presented the following technology areas as Technical Challenges (Reference 12:

a. discrimination;
b. missile guidance;
c. lethality;
d. kill assessment;
e. software integration; and
f. testing.

The computer-based model presented here is well-suited to the study of lethality issues. Of all avenues of research, computer simulation is a reliable and economic alternative to laboratory and range testing. This model can serve as a tool in support of lethality studies involving both the fragmentation process and fragment dispersion following a hit-to-kill interception. In this capacity, it can provide the scientific and technical background required to address a range of policy issues.

31. Although this study does not address specific intercept scenarios, several trends have emerged which deserve comment. The intuitive description of fragmentation and cloud size discussed in the previous section are borne out in simulation. Intercepts of Intercontinental Ballistic Missiles occurring hundreds of seconds before the scheduled RV impact are usually characterized by large debris fields. These fields can be several hundred to a thousand kilometres across. Assuming a constant fragment distribution gives fragment densities on the order of a few grams per square kilometre. These fall to the

Earth's surface after being decelerated by the atmosphere to relatively low terminal velocities. While the exact size and shape of the fragment field is sensitively dependent upon the intercept conditions, such low densities are usually typical of long-range intercepts.

32. Several avenues exist for future application of this model. Within the National Missile Defence arena, a study is under way to examine the relative risk posed by debris fields from a variety of hypothetical North American Continental Missile Defence scenarios (Reference 13). Within the Theatre Missile Defence arena, considerable controversy exists over the proper use of TMD to reduce collateral damage from debris. Experience gathered from the Patriot system used during the Gulf War has raised important questions. Some evidence indicates that the lower-tier Patriot intercepts resulted in significant collateral damage from debris (Reference 14). Patriot's proximity fuze warhead is intended to disable, not fragment, the incident Ballistic Missile (Reference 15). This results in the missile being intact or in a few very large fragments when it strikes the Earth's surface. This analysis tool can be used to compare the relative risk of proximity fuzing versus hit-to-kill technology for re-entry and midcourse intercepts.

33. Current TMD architecture studies call for a multi-tiered approach to missile defence. Systems such as Patriot and its follow-ons would provide low-altitude defence of point targets. Land and sea-based systems such as THAAD would provide high-altitude defence of area targets. Boost-Phase Intercept (BPI) systems would provide extremely early interception with the ballistic missile while still within the Earth's atmosphere. These earlier intercepts provide additional time for the debris cloud to diffuse, reducing the risk from falling fragments. BPI systems can even result in the debris falling back near the launch site. This model could be used to study the reduction in risk afforded by earlier missile interception.

34. The simulation model was developed in DAOR and is available for research and study purposes. Owing to the substantial computational overhead involved, it runs on a Sun Workstation configured for dedicated mathematical processing. Due to the amount of processing involved to produce debris field graphics and analysis, it is recommended that the model be used primarily within the directorate by experienced personnel.

IV. CONCLUSION

35. Current and near-term Ballistic Missile Defence systems emphasize the use of hit-to-kill interceptors to defeat ballistic missiles. These interceptors use the energy of motion between the interceptor and the missile to disable or destroy the ballistic missile. At speeds of several kilometres per second encountered in the missile regime, this energy is often sufficient to fragment the ballistic missile into many small fragments. These fall to the surface of the Earth to form a debris field. This raises questions of interest within the policy and strategy arenas. For example: what is the relative risk posed by falling debris? Can defence assets be allocated to control debris? What is the relative risk posed by falling debris, in comparison to an unintercepted missile?

36. This report describes the processes which produce a debris field, and presents a computer-based analysis tool which models the debris creation process. The fragmentation resulting from ballistic missile interception is modelled using information derived from laboratory and range testing. The fragment's fall to Earth is simulated using a re-entry model derived from ballistic missile and meteor re-entry physics. The model is at a level of detail sufficient for its use as a planning tool.

37. Although this report does not address specific intercept scenarios, several trends have emerged which are worthy of comment. Hit-to-kill interception is likely to produce many small fragments, typically weighing less than a few grams, and a few more massive fragments of a few kilograms. Fragments of the ballistic missile or Re-Entry Vehicle fall along their original ballistic trajectory, and so tend to fall to Earth in a cloud which surrounds the intended target location.

38. While the exact size and shape of the cloud are sensitively dependent upon the conditions of the intercept, some general trends are apparent. Hit-to-kill interceptions of Intercontinental Ballistic Missiles occur at altitudes of several hundred kilometres, within a Ground-Based Radar battlespace of several thousand kilometres extent. These

interceptions can occur hundreds of seconds before the Re-entry Vehicles would otherwise impact. The debris cloud from interception therefore spends several hundred seconds expanding about the RV trajectory at relative speeds of several kilometres per second. By the time the debris cloud is slowed by the Earth's atmosphere, it is usually several hundred kilometres across. The cloud settles to Earth at or near the intended target site, with an average fragment density of a few grams per square kilometre. This study has addressed only the physical process of fragmentation and debris field creation. Questions of relative risk arising from the nature of the fragmented warhead (chemical, biological or nuclear) have not been addressed here.

39. In summary, this model serves as a basic assessment tool, providing estimates of strewn debris fields resulting from ballistic missile intercepts. The constituent processes are modelled at a level of detail sufficient to augment strategy or policy studies, or to serve as a precursor to more detailed systems or engineering-level investigations.

40. The following recommendations are made for the use of this analysis tool:

a. an examination of the relative risk posed by debris from current lower-tier TMD systems used in peacekeeping or global contingency scenarios;
b. an examination of the relative risk posed by debris from proposed TMD systems in peacekeeping or global contingency scenarios, using TMD systems such as Patriot, THAAD and Boost-Phase Intercept systems; and
c. use of the model in support of scientific studies of kinetic energy lethality mechanisms.

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Several Ballistic Missile Defence Systems currently in development worldwide will rely on hit-to-kill interceptor technology to disable or destroy ballistic missiles and re-entry vehicles. Hit-to-kill interception at the very high speeds encountered in the missile regime will likely result in fragmentation of both the interceptor and the target missile. The fragments will then fall to Earth to form a debris field. This technology raises questions within the policy and strategy arenas. This Project Report describes the processes responsible for debris field formation. It also introduces a computer-based model which simulates the fragmentation process and the creation of a debris field. The model is intended as an analysis tool to support investigation for potential policy/planning questions, or to serve as a precursor to more detailed engineering studies.

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