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An examination of the military utility of long range hypersonic missiles

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Defence R&D Canada – Valcartier
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Abstract

This document summarizes the Operational Research (OR) support provided by the Defence Research and Development Canada – Valcartier OR group to the Capability Engineering for Hypersonic Airbreathing Weapons project. The main objective of the OR study was to examine the military utility of long-range hypersonic missiles (HMs). Firstly, the author presents an historical background on HMs development, the critical technology challenges that HMs are facing, and the main advantages of HMs. Secondly, an overview of the potential military utilities and applications of HMs is included. The potential applications and contributions of HMs are put into context, in a general manner, within the current environment and requirements of the CF, which is dictated by the Defence Policy Statement and the eleven Force Planning Scenarios. Finally, the author includes a quantitative analysis on the effectiveness of HMs to engage mobile time-sensitive targets. The hunt for transporter-erector-launcher vehicles during the First Gulf War is used as case study. The results of the analysis showed that HMs can be of great value in the engagement of time-sensitive targets.

Résumé

Ce document résume le soutien de Recherche Opérationnelle (RO) apporté par le groupe de RO de Recherche et développement pour la défense canada – Valcartier au projet Capability Engineering for Hypersonic Airbreathing Weapons. L’objectif premier de cette étude de RO est d’examiner l’utilité militaire des missiles hypersoniques (MH) à longue portée. En premier lieu, une revue historique du développement des technologies hypersoniques, les technologies critiques auxquelles font face les MH, ainsi que les principaux avantages des MH sont présentés. Par la suite, un aperçu des principales utilités militaires des MH sont énumérées. Les applications et les contributions militaires potentielles des MH sont ensuite mises, d’une façon très générale, dans le contexte canadien, c’est-à-dire, en tenant compte de l’Énoncé de la politique de défense de même que des onze Scénarios de planification des Forces. Finalement, une analyse quantitative de l’efficacité des MH pour l’engagement de cibles mobiles dites à facteur temps critique est aussi incluse dans ce memorandum. Le scenario de la chasse pour les véhicules de type transport-érecteur-lanceur durant la première guerre du Golfe a été utilisé comme cas test. Les résultats de l’analyse ont démontré que les MH seraient d’une grande utilité dans le processus de destruction de cibles à facteur de temps critique.

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Executive summary

Long-range hypersonic missiles (HMs) may be one of the transformational capabilities the military forces need to engage and defeat time-critical targets, and heavily defended, hardened or buried targets. In April 2005, an applied research project, entitled Capability Engineering for Hypersonic Airbreathing Weapons (CEFHAW), was initiated by Defence Research and Development Canada (DRDC) – Valcartier. The CEFHAW project is the first phase of a proposed three-phase program to develop, demonstrate, and validate a capability to evaluate and analyze enabling technologies of HMs (speed above Mach 5).

The members of the CEFHAW project requested Operational Research (OR) support from the DRDC Valcartier OR group to address the following questions:

- What are the potential military utility and applications of HMs?
- Where do these applications fit in the Canadian military picture?
- Can we determine valid and meaningful scenarios, from a Canadian Forces (CF) operational point of view, where HMs would be of interest?
- Is it possible to quantify the potential benefits of such technology over other options such as manned aircraft?

The general thinking about hypersonic technology is that it has the potential to revolutionize warfare by providing forces with the ability to take the fight to the adversary more quickly, at greater distances, and with greater firepower. Other characteristics justifying the various hypersonic research and development initiatives are the absence of a human crew and the high degree of survivability.

Considering all of the aforementioned advantages, the main military utilities envisioned for HMs are the following:

- Engagement of time-sensitive targets (TSTs), including both mobile and fixed or stationary surface targets;
- Attacking hard and deeply buried targets (HDBTs);
- Suppression of enemy air defence; and
- Serving as an additional defensive layer for an air defence system.

From a CF point of view, based on the Defence Policy Statement published in 2005, on the eleven departmental Force Planning Scenarios and on recent CF operations, it appears that the aforementioned HMs utilities are roles that will be required in future CF operations, in particular in the context of international security. Experience in

Kosovo and in the First Gulf War, which are the types of conflicts where the CF is envisioned to participate in the future, showed that engagement of TSTs (mobile missile launchers, bridges, aerodromes, government buildings, troops on the ground, etc.) and destruction of HDBTs (underground facilities) were key to the success of the mission. These elements are also extremely important in the on-going international campaign on terrorism where many situations of TST prosecution have been reported. In the Canadian and North American contexts, TST engagement may potentially be important to protect against maritime threats such as container ships seeking to deliver weapons of mass destruction using cruise missiles off the East or the West coasts.

In order to quantify the effectiveness of HMs in the engagement of TSTs, the author used, as a baseline scenario, the hunt for transporter-erector-launchers (TELs) that occurred during the First Gulf War, but assuming that HMs were available at the time to prosecute this type of mobile target. Note that there is no evidence that a single TEL was destroyed by the Coalition in the original conflict. A Monte Carlo simulation was developed by the author to model the conflict and various scenarios were run. The results show that using two HMs launch sites located at Prince Sultan Air Base (Al Khary, Saudi Arabia) and Incirlik Air Base (Adana, Turkey), the Coalition could have expected to destroy approximately 25 TELs by the end of the conflict, considering HMs speed and maximum range of Mach 6 and 1000 km respectively). With a maximum HM speed set to Mach 6 and a maximum HM range varying between 600 and 1200 km, the probability of TEL destruction varied between 0.142 and 0.359. As for the case where the maximum is set to 1000 km and the speed is varied from Mach 5 to Mach 8, the probability of TELs destruction is expected to be in the range of 0.286 and 0.491. It is also estimated that with the same concept of operations, a total of six strike aircraft would be required to fly simultaneously over the area of interest in order to obtain comparable results.

This study opens the door for more work on the subject, such as the development of more specific and detailed scenarios that can be used for the performance analysis tool that is being developed by the members of CEFHAW. Additionally, more quantitative analysis should be completed to compare existing options with HMs performing the aforementioned roles. Finally, a cost-benefit analysis should be considered to determine if it is worthwhile for Canada to invest further in research and development related to hypersonic technologies.

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Sommaire

Le Missile Hypersonique (MH) à longue portée est peut-être une des capacités militaires nécessaires pour engager et détruire des cibles dites à facteur de temps critique ou des cibles renforcées et profondément enfouies. En avril 2005, un projet intitulé Capability Engineering for Hypersonic Airbreathing Weapons (CEFHAW) a vu le jour à Recherche et développement pour la défense canada (RDDC) – Valcartier. Le projet CEFHAW correspond à la première phase d'un programme de trois ans visant à démontrer et valider un outil pour l'évaluation et l'analyse des technologies permettant le développement de MH (vitesse supérieure à Mach 5).

Les membres du projet CEFHAW ont demandé le soutien de l'équipe de Recherche opérationnelle de RDDC Valcartier pour aborder les points suivants:

- Quelles sont les utilités et les applications militaires potentielles des MH?
- Où ces applications se situent dans le cadre militaire canadien?
- Est-il possible de déterminer certains scénarios plausibles, du point de vue des Forces canadiennes (FC), dans lesquels, les MH pourraient potentiellement jouer un rôle?
- Quantifier, si possible, certaines des utilités militaires des MH en les comparant à d'autres options existantes, par exemple, des avions de chasse.

Une opinion partagée par plusieurs sur les technologies liées à l'hypervélocité est qu'elles pourraient fort bien révolutionner les guerres en permettant d'engager l'ennemi plus rapidement, à de plus grandes distances et avec plus de force de frappe. D'autres caractéristiques qui justifient les nombreux programmes de recherche et développement des MH est le degré élevé de survie (difficile à détruire à cause de leur vitesse) ainsi que l'absence de l'humain dans le système.

En tenant compte des avantages des MH mentionnés ci-dessus, les principales utilités militaires envisagées pour les MH sont:

- Engagement de cibles à facteur de temps critique (mobiles et immobiles);
- Destruction de cibles renforcées et profondément enfouies;
- Mise hors de combat des moyens de défense aérienne ennemie; et
- Servir de couche additionnelle dans un système de défense aérienne.

Du point vue des FC, en se basant sur l'Énoncé de la politique de défense, sur les onze Scénarios de planification des Forces et sur des opérations récentes des FC, il semble que les utilités des MH mentionnés ci-haut, pourraient se révéler importantes dans les opérations futures des FC, surtout dans le cadre de la sécurité internationale. Les expériences vécues au Kosovo et lors de la première guerre du Golfe, qui sont des conflits similaires à ceux auxquels les FC pourraient participer, l'engagement de cibles à facteur de temps critique (lanceur mobile de missiles, cibles fixes et de surface telles que ponts, aérodromes, édifices gouvernementaux, troupes ennemies au sol, etc.) et la destruction de cibles renforcées et profondément enfouies (complexes souterrains) ont été des éléments-clé pour le succès de ces missions. Ces deux rôles sont aussi omniprésents dans la campagne internationale actuelle contre le terrorisme où de nombreux exemples d'engagements de cibles à facteur de temps critique ont été rapportés. Dans les contextes canadien et de la défense de l'Amérique du Nord, l'engagement de cibles à facteur de temps critique peut aussi être très important pour la protection contre des menaces maritimes telles que navires porte-conteneurs prêts à une attaque aux armes de destruction massive utilisant des missiles de croisière.

Dans le but de quantifier les effets de l'utilisation de MH dans le processus d'engagement de cibles à facteur de temps critique, l'auteur a utilisé comme cas de base, la chasse aux véhicules de type transport-érecteur-lanceur (TEL) durant la première guerre du Golfe, en supposant que les MH existaient au moment du conflit. Il est à noter que lors de ce conflit, aucun TEL n'a été détruit par la Coalition. Une simulation de type Monte Carlo a été développée pour modéliser le conflit et plusieurs scénarios ont été exécutés. Les résultats ont démontré qu'en utilisant deux sites de lancement de MH situés à Prince Sultan Air Base (Al Khary, Saudi Arabia) et à Incirlik Air Base (Adana, Turkey), la Coalition aurait pu espérer détruire environ 25 TEL en prenant en compte une vitesse et portée des MH de Mach 6 et 1000 km respectivement. À une vitesse maximale de Mach 6 et une portée maximale variant entre 600 et 1200 km, les probabilités obtenues de destruction de TEL se situaient entre 0,142 et 0,359. Dans le scénario où la portée maximale était fixe à1000 km et où la vitesse variait entre Mach 5 et Mach 8, les probabilités de destruction de TEL estimées étaient entre 0,286 et 0,491. On a aussi calculé qu'en utilisant le même concept d'opération, six avions de chasse survolant simultanément la région d'intérêt seraient requis pour obtenir des performances similaires aux scénarios utilisant les MH.

Cette étude ouvre la porte à plusieurs autres travaux sur le sujet, tel que le développement de scénarios plus précis et plus détaillés pouvant être utilisés par l'outil d'analyse de performance présentement développé par les membres de CEFHAW. De plus, d'autres analyses quantitatives devraient être faites pour comparer les options présentement utilisées aux MH pour remplir les rôles mentionnés ci-dessus. Finalement, une étude coûts/bénéfices devraient aussi être faite pour déterminer s'il est pertinent et s'il vaut la peine que le Canada investisse davantage dans des projets de recherche et développement liés à l'hypervélocité.

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1. Introduction

1.1 Capability Engineering for Hypersonic Airbreathing Weapons

Long-range Hypersonic Missiles (HMs) may be one of the transformational capabilities that military forces need to engage and defeat time-critical targets, and heavily defended, hardened or buried targets. HMs possess a unique combination of speed, lethality, survivability, and range. In April 2005, an applied research project[1], entitled Capability Engineering for Hypersonic Airbreathing Weapons (CEFHAW) [1], was initiated by Defence Research and Development Canada (DRDC) – Valcartier.

The CEFHAW project is the first phase of a proposed three-phase program[2] to develop, demonstrate, and validate a capability to evaluate and analyze enabling technologies of HMs (speed above Mach 5). This capability will be applicable to a range of HM missions characterized by long-range time-critical engagements. The aim of the initial phase (CEFHAW) is to build, through modelling and experiments, an expertise in the fundamental physical processes for hypersonic flight, including aerothermodynamics and propulsion. This will allow the project team to begin modelling the individual flowpath components and the aerodynamics of the vehicle. Then, a basic version of a performance prediction tool for the flight of a HM using airbreathing propulsion will be developed.

1.2 Operational Research Support to CEFHAW

In recent years, there has been an increased demand for Operational Research (OR) support on new research and development initiatives at DRDC and on newer military technologies in general [2,3]. Scientists, researchers, and planners have realized that prior to spending considerable efforts and money on investigating (or purchasing) a new technology or system for the Canadian Forces (CF), it is extremely important to determine what would be the technology's role(s), if any, in the Canadian military context. With that in mind, the members of the CEFHAW project requested OR support from the DRDC Valcartier OR group to address the following questions:

- What are the potential military utilities and applications of HMs?
- Where do these applications fit in the Canadian military picture?

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[1] An Applied Research Project is a Defence Research and Development Canada program designed to advance the defence science knowledge base, investigate novel and emerging technologies and explore the military application of those technologies.

[2] The first phase is expected to last two years and the total program time is planned to be nine years.

- Can we determine valid and meaningful scenarios, from a CF operational point of view, where HMs would be of interest?

- Is it possible to quantify the potential benefits of such technology over other options such as manned aircraft?

In an attempt to address and answer these questions, this report is organized in six sections. Section 2 provides historical background on the HM development, presents some of the critical technology challenges that HMs are facing, and enumerates the main advantages of HMs. Section 3 presents an overview of the potential military utilities and applications of HMs. In Section 4, the possible applications and contributions of HMs introduced in Section 3 are put into the context of the current environment and requirements of the CF, which is dictated by the Defence Policy Statement (DPS) published in 2005 [4] and the Force Planning Scenarios[3] (FPSs) [5]. Section 5 includes a quantitative analysis measuring the effectiveness of the use of HMs in the engagement of mobile TSTs. The First Gulf War is used as the baseline scenario. Lastly, Section 6 summarizes the main conclusions.

Although there is some quantitative analysis provided in Section 5, this report looks at HM utility mainly from a qualitative perspective, examining its usefulness in a general manner across the DPS and the FPSs. One of the goals of this report is not simply to present findings, but also to provide tools for the reader to establish their own assessment of HM utility.

[3] The 11 FPSs were created in 2000. Presently, new scenarios are being developed by the department to reflect the new vision of the Chief of Defence Staff expressed in 2005. However, the author decided to use the old FPSs since the new scenarios will not be ready soon enough to meet the deadline of this OR study.

2. Background

2.1 Hypersonic Missiles

It is important to establish how HMs are defined in the context of this project. As defined in [6], the term "hypersonic" is associated with speeds that are highly supersonic. At first the term had no strict definition, but starting in the 1970s it generally came to refer to speeds of Mach 5 and above[4].

For the purpose of this report, HMs refer to missiles, launched from a standoff position, that can reach speeds between Mach 5 and Mach 8. The proposed concept could rapidly engage time-sensitive targets (TSTs) at high velocity with minimum preparation and provide on-demand and sustained precision firepower with tactical reach: 500 nautical miles (nm) in 10 minutes at Mach 6. More specific details about range, speed, and other characteristics regarding HMs will be presented later.

2.2 Hypersonic Development

The general thinking among United States (US) defence officials is that hypersonic technology has the potential to revolutionize warfare by providing their forces with the ability to take the fight to the adversary more quickly, at greater distances, and with greater firepower [7].

As a result of the benefits to be realized from hypersonic technology, important science and technology investments have been made in the US on various hypersonic technology initiatives in the past decade. These efforts were or are supported by the Department of Defense, the Defense Advanced Research Projects Agency (DARPA) and the National Aeronautics and Space Administration (NASA).

The Hypersonic Technology (HyTech) program [8,9], initiated in 1995 at the Wright Laboratory at Wright-Patterson Air Force Base, Ohio, was meant to develop and demonstrate air-breathing, storable-fuel (hydrocarbon), scramjet propulsion technologies for missile (and aircraft) applications that can cruise at Mach 8. For the HyTech program, the main application envisioned was a long range hypersonic cruise missile that is logistically supportable in a combat environment and that can defeat TSTs and hardened and deeply buried targets (HDBT). The US Air Force concluded ground tests in January 2001, when engineers successfully ran a scramjet engine at speeds of Mach 4.5 to 6.5 [7]. The engine used was the one developed by Pratt and Whitney under the HyTech program. At this time, HyTech continues to develop technologies in support of the Scramjet Engine Demonstration program (sponsored by DARPA and US Air Force) in addition to developing and maturing other hypersonic technologies [10].

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[4] The speed of sound is typically measured given a *standard atmosphere*. Under these conditions the speed of sound is approximately 343 m/s, 750 miles/hour, or 1207 km/h.

The US Department of Defense is also collaborating with the NASA on airbreathing propulsion technologies in support of the NASA Hyper-X activities [11]. The goal of the Hyper-X is to demonstrate, validate and advance the technology, experimental techniques, and computational methods and tools for design and performance predictions of a hypersonic aircraft powered with an airframe-integrated, scramjet engine. NASA believes that air-breathing hypersonic propulsion would enable unprecedented safe, affordable access to space, enabling new avenues of space exploration and exploitation [7].

Another program that existed in the US was the Affordable Rapid Response Missile Demonstrator (ARRMD), which began in 1998. The aim of ARRMD was the flight test demonstration of a long-range hypersonic cruise missile concept designed to meet the most effective set of performance objectives while constrained to a firm program affordability requirement [8,12]. The US Air Force originally planned to fly the HyTech engine under the ARRMD program. The aim of ARRMD, also led by DARPA, was to build and demonstrate a Mach 6-8 scramjet-powered, hydrocarbon-fuelled missile with a range out to 600nm to strike TSTs at a flyaway price of $200,000 [7]. The agency successfully completed Phase 1 of ARRMD in mid-2000 and decided to halt the program at that point.

Since 2002, the development of US hypersonic land attack missiles is being led by the Hypersonic Flight (HyFly) Demonstration program, sponsored by DARPA. The HyFly is derived from ARRMD and applied the propulsion technology and expertise available. The Office of Naval Research is partnering with DARPA in this four-year project, which is oriented towards the future needs of the US Navy [13]. The ultimate goal of the program is to demonstrate a vehicle range of 600 nm and a maximum sustainable cruise speed in excess of Mach 6. When cruising at a slower rate of Mach 4, the range would be extended to almost 800 nm.

There are also other very ambitious hypersonic technology initiatives currently on-going in the US such as the Falcon program (DARPA and US Air Force), the PASCAL program (DARPA) and the Army Hypersonic Engine Technology Demonstration program which entails the development and ground testing of a flight-weight hypersonic scramjet engine [10].

Hypersonic research efforts are in progress in many other nations across the world, mostly centered around missile technology for a variety of roles.

HyShot is a multinational research project managed by the University of Queensland, Australia Centre for Hypersonics, to demonstrate the possibility of supersonic combustion under flight conditions and compare the results of shock tunnel experiments with each other [14]. The system was first flown successfully on 30 July 2002, and it is believed by many to be the first successful flight of a scramjet engine.

Several countries including United Kingdom (SHyFE program – Sustained Hypersonic Flight Experiment), France, Germany, and Russia have all initiated development of Mach 4+ missile systems, with an eye to fielding operational systems eventually [7,15].

In Asia, India and Japan are the leading nations. India is investigating the possibility of developing a re-usable hypersonic missile while Japan has a reasonably advanced project called H2 Orbiting Plane Experiment [7].

The list of aforementioned hypersonic technology initiatives is not exhaustive but it shows that there is a vast interest for such technology in many countries around the world. A comprehensive review of the current international flight demonstration programs was developed for the recent Von Karman Institute lecture series on Critical Technologies for Hypersonic Vehicle Development [16].

2.3 Challenges in HM Development

The author acknowledges that a number of critical technical challenges are associated with the development of HMs. Perhaps the most challenging issue in HM development is the propulsion system. A tremendous level of thrust is required to propel a missile at hypersonic velocity (Mach 5 to 8). Additionally, a high specific impulse is needed for extended ranges such as the ones that are envisioned for the HMs (800 km to 1200 km).

Another technological problem plaguing HM development is the ability to deal with the extreme thermal environment. Aerothermic heating occurs by the friction of air passing the weapon's body. At Mach 4, the missile's body temperature can reach 1200 degrees Fahrenheit (°F). As the speed increases into the hypersonic velocity, the surface temperatures can exceed 2800°F at Mach 6, and 5600°F at Mach 8 [17]. There exist materials such as Iconel and Titanium that can handle the temperatures in the Mach-4 range [18] but no good missile materials that can survive the high surface temperatures encountered at hypersonic speed. A second aerothermic heating problem is keeping the missile's internal payload cool so it does not explode.

Additional technological issues include: stability, guidance and control, navigation, communications, the seeker and the payload (warhead) systems. A point that is worth mentioning is that all these challenges are issues when considered independently, but integrating all the subsystems in a larger system may represent an even more complex problem.

The objective of this report is not to explain how the aforementioned challenges will be mastered and solved but rather to present potential applications of HMs, when fielded. For this reason, the author assumes that the engineering challenges will be overcome and that HMs will exist in the future in the 2020 timeframe.

2.4 Advantages of Hypersonic Missiles

Before determining potential military utilities of HMs, it is important to clearly identify their main advantages. HMs offer the following advantages:

- Speed/Rapid Response Time: Decreased response time is certainly one of the advantages of HM. Considering that a F-18, cruising at a Mach 0.85 (1025 km/h), covers approximately 85 km in 5 minutes, a HM flying at Mach 8 can cover about 9.5 times that distance (805 km) in the same period of time. The speed and range of HMs allows them to be launched well outside any threat envelopes and still impact the target with the same timeliness of an aircraft loitering close to the target [18]. This characteristic of HMs makes them an excellent option to engage TSTs such as mobile Scud launchers seen during the first Gulf War or any targets requiring immediate response;

- Penetration and Destructive Power: A second advantage, described in [19], is the inherent kinetic energy of a hypersonic missile, which magnifies its penetrating power. This phenomenon makes HMs well suited to attacking HDBT such as command and control bunkers or weapon storage facilities, which are among the toughest targets to destroy. Obviously, this advantage is only valuable if the munitions of the HM are a tailored warhead that can exploit the kinetic energy of the missile by being integrated into a penetration assembly;

- Survivability: A third advantage of HM is the high degree of survivability that results from hypersonic speed at high altitude. High speed reduces the chances of the missile being detected and countered by surface-to-air missiles. The use of HMs also increases the warfighter survivability due to the capability to engage and destroy the threat outside the "keep out" area. These characteristics make the HM extremely difficult to defeat and enables rapid mission planning and a high probability of mission success;

- Range: The ability to engage the enemy at long range, from a standoff position, is a very attractive characteristic of HMs. The range of the HMs envisioned in this project is 800-1200 km, which would allow attacking of critical targets deep behind enemy lines at any time during a conflict, even during the early stage of the conflict; and

- No Crew Risk: Finally, the absence of a human crew represents an advantage for the HM since crew safety is no longer a consideration. When working in a hostile environment where the enemy defence system is still active, the absence of humans avoids the politically unattractive risk of putting humans in dangerous situations by eliminating the risk of casualties. Additionally, unlike manned aircraft, HMs can operate in a nuclear, biological, or chemical environment.

The next sections present the potential military utilities and applications of HMs and put them in a Canadian context.

3. Potential Roles for HMs

This section presents the main military applications for HMs determined as a result of a literature review and discussions with military personnel. The aim of the section is to provide the reader with an overview of the potential military utility of HMs. The applications listed are very general in nature and could be broken down into more specific tasks and studied in more detail in a future work. The author acknowledges that the list is not exhaustive, and that it is only meant as a starting point for discussion. Certain applications could arguably be added or re-categorized, depending on perspective or the area of interest. The list of applications, discussed in the following subsections, is depicted in Table 1.

Table 1: Military Applications of HMs

A.	Engagement of Time-Sensitive Targets
	1. Mobile TSTs 2. Fixed TSTs
B.	Hard and Deeply Buried Targets (HDBTs)
C.	Suppression of Enemy Air Defence (SEAD)
D.	Additional Defensive Layer for an Air Defence System

3.1 Engagement of Time-Sensitive Targets

The primary military objective of most of the hypersonic initiatives mentioned in Section 2 is to defeat TSTs. In general terms, TSTs can be defined as targets requiring immediate response because they pose (or soon will pose) a serious and imminent threat capable of inflicting casualties on friendly forces and civilians. TSTs are fleeting targets of opportunity, highly lucrative and high-payoff (normally very high on the commander's priority list of targets) [20,21]. TSTs have a limited window of vulnerability or engagement opportunity during which they must be found, located, identified, targeted, and engaged. TSTs can be mobile or fixed targets, on land or sea. Note that in this paper, there is no distinction between TSTs and time-critical targets (TCTs), although, some papers refer to TCTs as a subset of TSTs [22].

3.1.1 Mobile Time-Sensitive Targets

Mobile TSTs are targets that have a very limited window of engagement opportunity because they can move and hide quickly. For these reasons, such threatening targets required a rapid, if not immediate, response. Normally, such mobile targets are not hard to destroy if they can be hit. However, they are difficult to find and, once they have been found, they can move before they can be hit. Table 2 presents a list (not exhaustive) of the most common mobile TSTs.

Table 2: Examples of Mobile Time-Sensitive Targets

A.	Enemy forces in transit
B.	Terrorists fleeing in a vehicle
C.	Mobile theater missile launcher
D.	Mobile surface-to-air missile launcher
E.	High-value military cargo
F.	Mobile command and control vehicles and facilities
G.	Small naval craft

To illustrate the difficulties of destroying mobile TSTs, consider the example of a vehicle transporting terrorists that will soon pose a serious threat. Suppose that intelligence sources indicate that a vehicle transporting terrorists is at a certain location. For this example, it is assumed that there is no tracking capability. One of the means of attacking the target is to send an air weapon system[5] that will fly to the initial vehicle position, find, identify, and engage the moving target. Once at the initial vehicle position, the weapon system can perform the find/identify/engage cycle and drop munitions to destroy the target.

The size of the area that the weapon system has to search once it reaches the initial reported position of the target, depends on the speed of the fleeing target and on the time elapsed before the air weapon system arrives at the initial vehicle position. The problem is that if the weapon system does not get to the initial vehicle position very rapidly, the probability that the enemy vehicle will be found is very low. This can be explained by the fact that the size of the search area increases with the square of how far the vehicle travels during the elapsed time, assuming that the vehicle can move in any direction.

Figure 1 illustrates this phenomenon, for an enemy moving at a constant speed of 25 km/h and assuming that the air weapon system leaves immediately after the position of the vehicle is provided by intelligence sources. The *x*-axis corresponds to the flying time, in minutes, to the enemy vehicle cue position and the *y*-axis, the area to search, expressed in square kilometres.

A second problem occurs if the entire area cannot instantaneously be searched when the weapon system arrives. While the weapon system is finding the target, the search area continues to grow because the vehicle is still moving. For example, if the weapon system arrives 10 minutes after the vehicle departs, the total search area is approximately 55 km^2 at that particular time, but if the target is not found immediately, the area continues to increase (it quadruples 10 minutes later).

[5] In this situation, weapon system can be an aircraft, an unmanned air vehicle or a missile.

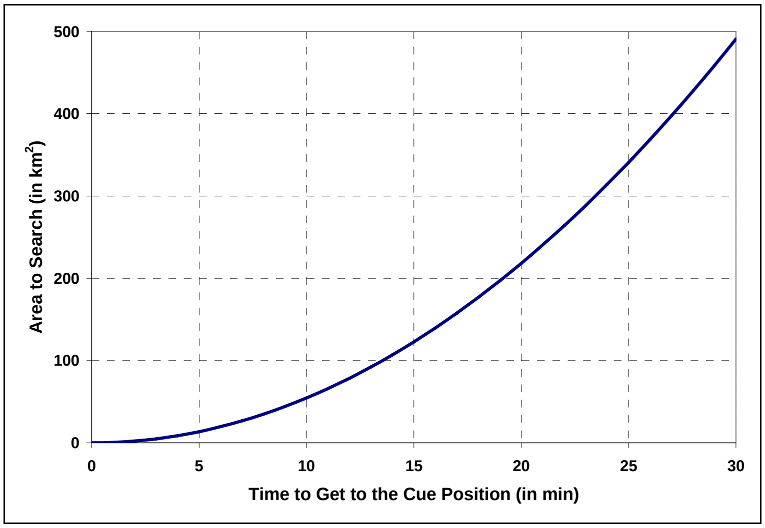

Figure 1: *Area to Search as a Function of Time to Get to Initial Position – Vehicle Moving at 25 km/h*

Since the mobile target can be moved during the flight of the weapon system, it is obvious that the faster the weapon system arrives at the initial launch position, the better are the chances to find the target and therefore, to destroy the target. Figure 2 shows the probability of finding a target, in less than 30 minutes, as a function of the time to get to the initial launch position. In this example, the vehicle is moving at 25 km/h, and the effective search rate of the weapon system is 1.67 km^2/min.

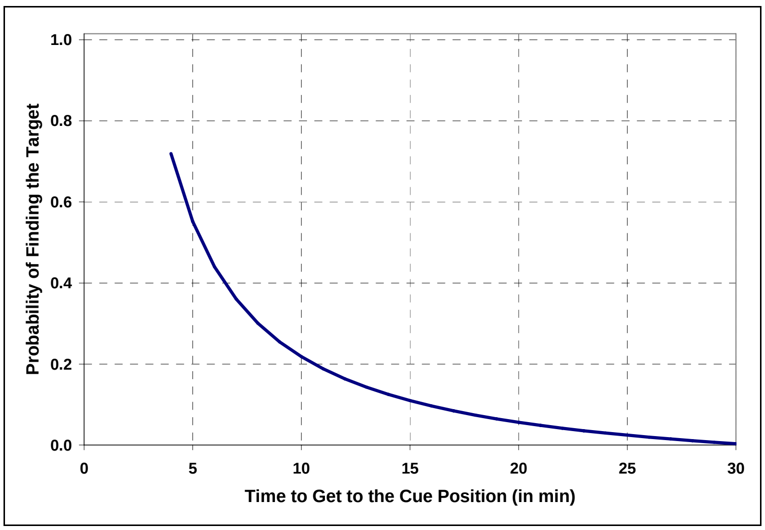

Figure 2: *Probability of Finding the Target in Less than 30 Minutes – Vehicle Moving at 25 km/h, Effective Search Area 1.67 km^2/min*

A well-known historical example of mobile TST engagement is Transporter-Erector-Launchers (TELs) hunting that happened during the First Gulf War. Following Scud launches from the Iraqis, which were detected by airborne sensors, attack aircraft were concentrated in the launch area to search for and attack suspect vehicles. The strategy of employing aircraft as weapon system was not a success story, since no destruction of mobile launchers was confirmed during the conflict. Once the coalition aircraft reached the launch position, the enemy vehicle had already disappeared to a hidden location. The time it took for the air weapon system to locate the TELs simply exceeded the time it took for the Iraqis to shoot and scoot. In order to obtain a reduced time to target, meaning better chances of finding and destroying TSTs, several on-station aircraft would have been be required. This type of engagement, i.e. mobile TSTs and in particular TELs, will be discussed and addressed in further detail in a more quantitative way in Section 5.

The requirement for quick response makes HMs a very attractive option for mobile TST engagement. HMs can be fired from a standoff position outside a heavily defended target area and yet reach the mobile target before they can move any significant distance.

3.1.2 Fixed or Stationary Surface Time-Sensitive Targets

Time-sensitive targeting does not only mean engaging mobile targets. In fact, TSTs may also be fixed or stationary targets. Under certain circumstances, ordinary fixed surface[6] targets may be classified as time-sensitive if they present a lucrative opportunity that the commander determines is a priority. In order words, a fixed or stationary TST is an immobile target that it is better to strike today rather than tomorrow. Table 3 contains examples of fixed surface TSTs.

The tremendous speed offered by HMs, which considerably reduces the time to reach the target, makes HMs a primary choice for fixed surface TST engagement. HMs allow rapid target destruction from a very long range (standoff position), if required. Obviously, not all fixed TSTs shall be engaged with HMs. For this particular role, they should rather be used as a complement to existing options. For instance, there are situations where fixed TSTs should be engaged by an aircraft located near the target position, and equipped with appropriate munitions.

3.2 Attacking Hard and Deeply Buried Targets (HDBTs)

In the literature, a very widespread military utility and objective behind hypersonic development is the attack of HDBTs. Targets that are fixed but hard and deeply buried, are called HDBTs. In general terms, HDBTs refer to all types of intentionally hardened and strengthened targets, either below or above ground, that are designed to minimize the effects of kinetic weapons. Examples of HDBTs are presented in Table 4.

[6] In this document, the term "surface targets" refers to targets that are not heavily defended, hardened or buried.

Table 3: Examples of Fixed Surface Time-Sensitive Targets

A.	Operational-level command centers that, once their location is determined, must be destroyed quickly to allow further friendly force actions
B.	Nuclear, chemical biological weapons depots, when transportation of the stored weapons is imminent, or if hidden, once they are detected
C.	Fixed surface-to-surface missile (SSM) sites, when detected and threatening to launch
D.	An enemy airfield may become a TST if it is determined, through intelligence sources, it will soon support aircraft equipped with weapons of mass destruction
E.	Aircraft on the ground (in preparation for striking)
F.	A bridge, previously left standing to channel enemy movement, may become a fixed TST once the commander determines it is time to destroy it and seal off an avenue of escape
G.	Other critical land navigation infrastructures, such as roads and rail lines, for movement of forces
I.	Terrorist camps

In the early twenty-first century, the existence of deeply buried underground facilities has emerged as one of the more difficult operational challenges facing military forces. In the United States for instance, military planners have expressed particular concern that states and organizations may use these facilities to manufacture and store weapons of mass destruction. Buried deep underground, these stores, along with command and control centres for them, could pose a serious threat to the United States and allies. The need for attacking HDBTs has also been part of previous conflicts. It is reported that during the First Persian Gulf War, ten percent of the 18,200 sorties flown by coalition aircraft were aimed at the critical war-making capabilities that are typically contained in underground facilities [23].

Conventional explosive-filled weapons are relatively ineffective in destroying large underground reinforced concrete facilities. The problem with the use of conventional weapons against HDBTs is that the depth and hardness of the targets can exceed the physical ability of the weapon to pass through tens of meters of rock and rubble.

The high penetration and destructive power of the HM due to its inherent kinetic energy, makes HMs a potential option for such engagement. As an example, since the kinetic energy of an object is directly proportional to the square of its velocity, an object striking at Mach 8 generates 64 times the force of an object of the same mass striking the target at Mach 1.

Table 4: Examples of Hard and Deeply Buried Targets

A.	Underground complexes housing biological/chemical/nuclear weapons production, assembly or storage facilities
B.	Infrastructures to conceal and protect national leadership, military and industrial personnel
C.	Hardened aircraft shelters
D.	Belowground command, control, and communications facilities
E.	Underground infrastructure storage of weapons' stockpiles and military equipment, such as theater ballistic missiles, TELs, etc.
F.	Long networks of underground pipes with passageways sufficiently large to move military troops and equipment
G.	Underground critical communications nodes
H.	Terrorists hidden in caves and tunnels

The munitions requirements for hitting mobile or fixed TSTs are considerably different than they are for HDBTs. Obviously, to be valuable for HDBT destruction, the munition of a HM should be a tailored warhead that can exploit the kinetic energy of the missile by being integrated into a penetration assembly for deeply buried targets.

It is important to note that, although some of the aforementioned HDBTs must be disabled quickly in any conflict, the rapid response provided by the high speed is not one of the primary characteristics that make HM an interesting option for attacking HDBTs (unlike for TSTs engagement where quick response is necessary). It is rather the high penetration power and the long range that are required for mission success.

3.3 Suppression of Enemy Air Defence (SEAD)

Experience has shown that achieving and maintaining the required degree of control of the air, either by having a favourable air situation, air superiority, or air supremacy, is a prerequisite for all war-winning operations, whether at sea, on land or in the air. When faced with an enemy who has a strong surface-to-air defence system, defence suppression can greatly reduce loss rates and help sustain offensive air action. One of the means to obtain any degree of control of the air is to prosecute offensive counter-air operations, which include SEAD.

SEAD is that activity designed to destroy, neutralize or temporarily degrade enemy air defence systems in a specific area by physical attack and/or electronic warfare to enable air operations to be conducted successfully [24]. Target sets include radars and other sensors, anti-aircraft artillery batteries and surface-to-air missiles. All surface-to-air systems have certain inherent potential weaknesses: they are finite and normally have flanks; they are oriented towards the expected approach routes of the enemy; they are rarely equally strong throughout their width and depth; and they are either fixed or relatively immobile. Tactics and systems to perform SEAD are designed to exploit these potential weaknesses through speed, penetration, flank attacks, exploitation, and systematic reduction from the rear.

In the literature, it is mentioned that hypersonic and cruise missiles would be an excellent choice for neutralizing enemy air defences [25] because of their ability to exploit the aforementioned weaknesses. US planners believe that changes in technology, particularly information technology, coupled with the advent of precision standoff weapons such as HMs, will make it possible, in the future, to conduct the SEAD mission more effectively [26].

The weapon characteristics that are sought for SEAD are speed, range, and survivability. SEAD is normally performed at the beginning of a conflict, when enemy defensive systems are still active. Another advantage that makes HM a valuable option for SEAD is the absence of a human crew. The use of such standoff weapons for SEAD, would allow the force to take down and disable rapidly the enemy's air defence system in such a manner that it would not expose itself or allies to any risk.

The author realizes that SEAD is a much more specific role than the previous two applications mentioned (engagement of TSTs and HDBTs), and that because of the types of targets (fixed or relatively immobile – surface-to-air missiles, radars, sensors, anti-aircraft artillery batteries, etc.), it could have been incorporated in one of the previous two aforementioned military applications. However, SEAD is discussed in a separate subsection because the primary characteristics sought for this role (speed, range, survivability, and absence of humans), differ from the others.

3.4 Additional Defensive Layer for an Air Defence System

In the literature, some proponents of hypersonic technologies suggest that HMs can serve as an additional defensive layer for an air defence system.

For example, a research paper sponsored by the United States Army, which concentrates on evaluating the advantages and measures the potential military utilization of hypersonic technology [27], proposed a three-layered defence against enemy missiles formed of scramjet (i.e. hypersonic) missiles, ramjet missiles and fixed wing fighters. A vignette envisioned by the authors of the document is to locate scramjet missiles off the coast of North Korea for a defensive attack, to prevent a cruise missile attack from North Korea on the US Eastern Seaboard.

In another document [28], the author discusses a hypothetical scenario involving a low-flying Mach 1 cruise missile, equipped with a nuclear type warhead, attack on Washington, DC. In that case, the conclusion was that a hypersonic missile launched from near Washington with a velocity of Mach 7 after boost could make the intercept before the missile reached within four miles of the coast.

Finally, it is shown in [29] with mathematical calculations and simulations that the faster the interceptor can fly, the greater are the trajectory options available to the defence to enable an engagement opportunity. The performance of the interceptor is key to defining the interceptor's trajectory geometry. Performance in this context refers to the energy content of the interceptor or in other words, how fast the interceptor is flying. If the intercepting missile is fast then there are more opportunities to shoot down the threats. Having more opportunities gives a higher chance of success. Additionally, the paper suggests that if the interceptor is really fast, e.g. in the hypervelocity regime, then it can be shown that the threat can be intercepted at an early phase such as the boost phase. This would substantially increase the chances of negating the threat.

3.5 Comments

In this section, the author enumerated a series of potential uses of HMs and hypersonic technology. Obviously, it is important to realize that for these applications, HM is not the only technology necessary. All of the applications require an integrated system of technologies and different concepts of operations than the existing ones. Although new technologies are necessary, they alone cannot fulfill the different roles. As an example, for the TST engagement, improved sensors for detection and tracking capabilities, information passing and processing technologies and automatic target recognition capability are all technologies that will have to be enhanced for the HMs to be part of the TST engagement solution.

4. Hypersonic Missiles in a Canadian Context

In February 2005, the Chief of the Defence Staff (CDS) initiated the implementation of the new CF vision as articulated in the DPS. The document represented a significant change for the CF. It was the first review of Canada's defence policy in more than ten years and it defined a new policy that was firmly grounded in the realities of the post-Cold War, post-September 11th world.

Based on the new DPS, the department created a group composed of Directorate of Defence Analysis staff and force development organizations across the CF and the Department of National Defence (DND) to develop scenarios that describe the sets of circumstances in which the CF expects to be used. The aim is to use the scenarios to identify existing and emerging operational capabilities that would enable the CF to realize the CF vision, as well as to articulate an operational capability investment/divestment strategy. When completed, the scenarios will also be utilized to facilitate the institutionalization of capability-based planning within the CF and DND, and to identify capability gaps.

Although they would be of great value for this study, these scenarios were not fully available at the time this work was done[7], so the author had to base the work on the existing eleven FPSs [5] and on the DPS, which are very generic in nature. Figure 3 contains the eleven FPSs.

It is indicated in the DPS that the CF will continue to perform the following three broad roles:

- Contributing to international peace and security;
- Protecting Canadians; and
- Defending North America in cooperation with the United States.

This section contains a very general discussion on where, in the future, hypersonic weapon systems may have a significant contribution with regards to these three roles. It examines the utility of HMs across the eleven FPSs, the DPS, and on recent historical CF operations and involvements. Note that it was considered by the author that FPSs #3, #5, #6, #9 and #11 are associated with the CF contribution to international peace and security (International Security Context), FPSs #1, #2, #4, #7 and #8 are related to the CF role of protecting Canadians (Domestic Context) and finally, FPS #10 to the defence of North America in cooperation with the United States (North American Defence and Security Context). Past examples where HMs could have been used are also described in the section.

[7] A draft version of only 9 out of 17 scenarios was developed when the study presented in this report was conducted.

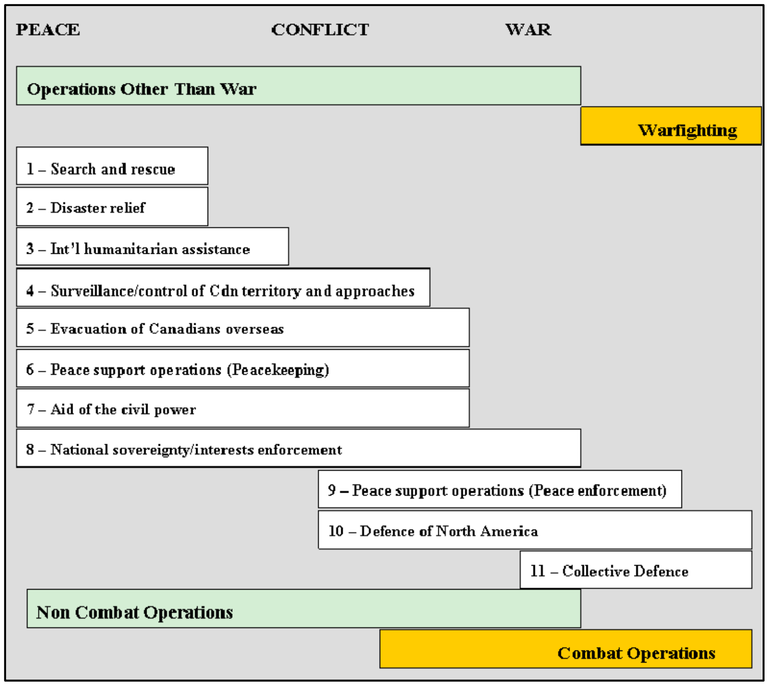

***Figure 3:** Departmental Force Planning Scenarios*

4.1 International Security Context

It is clear from the CDS priorities that in the future the CF will remain capable of participating in a wide range of operations overseas, particularly when dealing with the complex and dangerous environment of failed and failing states. These include combat operations, such as those conducted during the Kosovo air campaign and in Afghanistan.

4.1.1 Major International Coalition

The DPS states that the CF will continue to play an active role in international security by maintaining their contributions to international institutions such as the United Nations (UN) and the North Atlantic Treaty Organization (NATO). It is therefore expected that the CF will be involved in the future in multinational conflicts such as the ones experienced in Kosovo and Iraq (First Gulf War), conflicts similar to Scenarios 9 and 11 in the FPSs.

Fixed Surface TST Engagement in Kosovo: Canada's efforts to resolve the crisis spanned the full spectrum of conflict and operations. Canada's military was praised for its effective contribution to the air campaign. As part of the air campaign in Kosovo, the CF aircrews worked hand-in-glove with those of other NATO forces. Eighteen CF-18 aircraft of the CF flew combat missions from the NATO base in Aviano, Italy [30]. The CF pilots flew approximately 10 percent of all the sorties flown by the Coalition against Yugoslavia. Flying in the skies over Kosovo and

Serbia, the aircraft was primarily employed in the attack role dropping both conventional and precision guided munitions [31]. Canadians were responsible for the destruction of many fixed TSTs including: bridges over the Danube, aerodromes, Serbs troops on the ground, and military equipment such as surface-to-air missile launchers [32].

Mobile TST Engagement in Kosovo: In Kosovo, one of the Coalition's missions was the engagement of mobile TSTs, which were mostly dispersed ground forces. Some documents [37] indicate that the Coalition strike aircraft part of the engagement of mobile targets had very limited success during the crisis. Amongst the reasons evoked for this failure was the slow response to reconnaissance data, which included the long time it took to attack the targets, which is an aspect that HMs can potentially improve with their great speed.

Fixed Surface TST Engagement during First Gulf War: In 1990-1991, Canada was one of the first nations to agree to condemn Iraq's invasion of Kuwait and it quickly agreed to join the U.S.-led coalition. After the UN authorized full use of force in the operation Canada sent a CF-18 squadron with support personnel. Canada's planes were integrated into the coalition force and provided air cover and attacked time-critical ground targets.

Mobile TST Engagement during First Gulf War: The engagement of mobile TSTs was also an important role that the Coalition had to fulfill during the First Gulf War. In particular, mobile missile launchers known as TELs were used to launch Scud missiles at Israel, Saudi Arabia and Bahrain. Such vehicles were capable of moving quickly from hidden sites, firing and then hiding again before an air attack could be mounted. One of the means employed to reduce the Scud threat was to destroy the TEL after the missiles were launched. The hunt for TELs was actually identified as one of the rare Coalition failures during the conflict as there is no technical evidence a single TEL was actually destroyed by air or special forces attack during the war. The use of aircraft as the attack asset was not successful due to the delay between the time the moving targets were identified and the time it took for the strike aircraft to fly to the last known location of the targets. A discussion on the subject and a quantitative analysis on the effectiveness of using HMs for mobile TST engagement are included in Section 5.

Destruction of HDBTs during First Gulf War: As mentioned in Section 3, the need for attacking HDBTs, which could be fulfilled by HMs, has also been part of previous conflicts, such as the First Gulf War, where approximately 1,820 sorties flown by coalition aircraft were aimed at the critical war-making capabilities that are typically contained in underground facilities.

SEAD during First Gulf War: Concerning the SEAD capability, which could also be provided by HMs, it is at this time a more specialized capability maintained by larger air forces and not considered core to the CF. However, this does not mean SEAD is not important; it may actually be essential when operating against a robust Integrated Air Defence System (IADS). The Iraqi IADS encountered during the Gulf War was a robust, dense, overlapping, integrated and lethal system. The fact that the Coalition established a favourable air situation, using capabilities such as SEAD, was a key factor for the success achieved during the Gulf War.

Importance of TSTs for NATO: The NATO nations attach a high importance to the engagement of mobile TSTs. In fact, one the main objectives of the Maple Flag Exercise[8] held in 2005 was to prosecute moving TSTs [38,39]. The mobile targets included a boat and land-moving vehicle that can simulate many threat types such as terrorists using a small, fast-moving boat or a roaming surface-to-air missile launcher vehicle as seen during the First Gulf War. HMs could potentially, in the future, fulfill this role.

4.1.2 International Campaign Against Terrorism

Based on the DPS, it is likely that there will be no decline in the future demands for CF overseas operations similar to the ones conducted in Afghanistan. The attacks of September 11, 2001 ushered in a global campaign against terrorism. This international effort draws on contributions from many countries, including Canada.

Using HMs for the engagement of TSTs (both mobile and fixed surface targets) as well as for attacking HDBTs can be of great value in the current campaign against Al Qaeda and like-minded groups.

Fixed Surface TST Engagement in Afghanistan: Many situations of TST prosecution in Afghanistan have been reported. For instance, a demonstration of fixed surface TST engagement occured when a B-52 bomber put bombs on target within 20 minutes of a call for assistance [32]. The allied forces, who were riding on horseback, discovered a Taliban military outpost with artillery, barracks, and a command post. Although the Taliban force was quiet at the time, the allied commander identified the outpost as a stronghold. The commander asked for coalition aircraft to strike the target within the next few days. A combat controller notified the Combined Air Operations Center, and since the target lay in an already established engagement zone, the Combined Air Operations Center alerted a B-52 overhead. The B-52 struck the outpost 19 minutes after the initial call.

Mobile TST Engagement in Afghanistan: Most mobile TSTs in Afghanistan are terrorists such as Al Qaeda and Taliban leaders. Early in the campaign, US operators believed they had Mullah Omar, the Taliban's principal spiritual leader, in their sights. As reported in the New Yorker [33] a Hellfire-armed Predator was patrolling the roads south of Kabul on the first night of the war. The Predator identified a group of cars and trucks fleeing the capital as a convoy carrying Mullah Omar, the Taliban leader. The "shoot-do not shoot" decision was attributed to officers on duty at the headquarters. The Predator tracked the convoy to a building where Omar, accompanied by a hundred or so guards and soldiers, took cover. The precise

[8] The Maple Flag Exercise is a six-week international air combat exercise held annually at 4 Wing Cold Lake, Alberta. The objective is to provide relevant training that will prepare aircrews, involved in large package coalition forces, for the future battlescape. The exercise is one of Canada's contributions to making NATO a strong, combat-capable and ready force.

sequence of events could not be fully learned, but intelligence officials have said that there was an immediate request for a full-scale assault by fighter-bombers. At that point, the commander did not order an attack on the target, not convinced that it was the right decision. An operative on the ground later confirmed that Omar and his guards were in the convoy tracked by the Predator. Although, the decision at the end was not to destroy the target, this example and the previous one show the need for TST engagement in operations such as the one conducted in Afghanistan, in which the CF may well be involved in the future.

Destruction of HDBTs in Afghanistan: In the current deployment to Kandahar, Afghanistan, the CF land and special operations forces are involved in numerous combat operations alongside allied forces, hunting down members of the Taliban and Al Qaeda in the Afghan mountains. In this ongoing military campaign, time is of the essence, i.e. the Coalition has to engage targets quickly after intelligence sources report potential targets. In addition, firepower is also necessary to engage the opponents, who very often make use of hardened underground facilities. U.S. defence officials estimate that there are hundreds, if not thousands, of caves, tunnels, aqueducts and bunkers in the mountains and deserts of Afghanistan, the legacy of centuries of warfare and of an ancient farming technique that relies on underground water supplies [34]. Found primarily in eastern and southern Afghanistan, the hideouts include natural limestone caverns and tunnels, and man-made passageways. This network of mountain caves offers an ideal shelter to Taliban and Al Qaeda forces and leaders. The destruction of those targets, in this case enemy leaders hiding in hard, deeply buried places, requires some characteristics that are intrinsic to HMs.

4.2 Domestic Context

In the past, Canada has structured its military primarily for international operations, while the domestic role has been treated as a secondary consideration. This is not the case with the new DPS, where an important emphasis is put on protecting Canada and Canadians.

In the domestic context, the current planning scenarios do not present many situations that require HM capability. An important role that the CF has to play in the domestic context is to conduct search and rescue missions (FPS #1). In this case, the capabilities required for such missions cannot be provided by HMs. The same logic is valid for disaster relief scenarios (FPS #2), such as floods, ice storms, forest fires, hurricanes, and aid to civil power scenarios (FPS #7), including assisting other government departments in deterring illegal fishing, countering drug smuggling, intercepting ships carrying illegal migrants and protecting our environment. Again, in these situations, the military utilities mentioned in Section 3 are not sought for the success of such operations.

However, threats to Canada's sovereignty and territory are wide ranging and complex, and it is impossible to predict with certainty the precise forms they will take even five years from now. It is indicated in the DPS that one of the most critical security threats may be maritime threats such as a ship carrying a dirty bomb into Halifax harbour.

Another example included in the DPS is that of terrorist groups seeking to acquire the means to strike using not only hijacked airliners, but also, cruise missiles fired from container ships or other platforms off our coasts.

For example, one can envision a scenario where a container ship, located in the Atlantic Ocean and moving towards the east coast, is planning to deliver weapons of mass destruction on Canadian soil, using cruise missiles. To prevent the catastrophic consequences resulting from such a scenario, not only will the CF have to increase on-water patrols and aerial surveillance to detect the threat before it hits, but it will also have to possess a system able to rapidly engage the target. At this time, aircraft assets flying from one of the CF bases would probably be the way to engage the targets. However, it is expected that with launch sites strategically located, the HMs would engage the TSTs much faster than strike aircraft.

Another important point in the DPS is the need to be able to ensure sovereignty and security in the Arctic as activity in the North continues to rise. It is expected that air traffic over the high Arctic will increase, and climate change could lead to more commercial vessel traffic in Canadian northern waters. These developments will not result in the type of military threat to the North seen during the Cold War, but they could have long-term security implications. Adversaries could be tempted to take advantage of the new opportunities unless Canada is prepared to deal with asymmetric threats that are staged through the North. The Northern part of Canada is vast with a very low population density. Aerial surveillance bases and units will be dispersed in this huge territory. Threats to Canadian sovereignty will probably not demand an armed and lethal response but they will likely require a rapid response. One might envision scenarios where high-speed long-range systems would be necessary to fly in the North where a potential threat has been identified, and then deploy sub-munitions capable of engaging the target if required or just to patrol and watch closely the target. These are hypothetical scenarios since such situations have never been experienced, but there is a chance that similar scenarios will occur. This concept could potentially be applicable for search and rescue scenarios where a rapid deployment to the incident scene of sub-munitions (such as a mini-UAV) capable of finding survivors could make it easier for helicopter (or other assets) to pick them up when it arrives.

4.3 North American Defence and Security Context

Within the North American context, the CF will continue to defend and protect North America in cooperation with the United States. This has been done and will continue to be done via the North American Aerospace Defence Command (NORAD), which is a bi-national military organization established in 1958 by Canada and the United States to monitor and defend North American aerospace. NORAD operates a network of ground-based radars, sensors and fighter jets to detect, intercept and, if necessary, engage aerospace threats.

NORAD's mandate has always been to respond solely to aerospace threats. However, in May 2006 a decision was made by the United States and Canada to renew NORAD and to expand NORAD's mandate to take on a maritime surveillance and warning role

[35]. This means that, from that point, protection and response to maritime threats such as the previously mentioned TST engagement scenario involving a container ship seeking to strike using cruise missiles, will likely fall under NORAD's mandate. The threats in this scenario are comparable to the ones presented in FPS #10, a scenario involving a superpower nation who has effective military force with a vast array of modern weapons at its disposal and is threatening to use its naval assets to attack North America with submarines and cruise missiles. It seems likely that HMs may be able to fulfill some of capability requirements required to prevent such attack.

Although the ballistic missile threat to Canada is not currently considered to be high, joint Canadian and American intelligence estimates suggest that in the coming years the range and accuracy of ballistic missile technology available to potential proliferators will improve, weapons of mass destruction proliferation will continue and the threat to Canada and Canadian interests could increase. The DPS stipulates that Canada along with United States will seek to develop new, innovative approaches to defence cooperation to better meet the threats to both countries. In the future, one of these initiatives could very well be HMs incorporated in a ballistic defence system to prevent missile attack on North American soil. United States planning for ballistic missile defence aims to use a layered approach to intercept missiles by using land (large interceptor rockets or mobile launchers), sea (missile ships), and air (airborne laser) platforms to shoot down incoming missiles [36]. Air- and sea-based platforms can be positioned close to the launch site of a hostile missile and can intercept it during the boost phase, i.e. period just after a missile's launch. The use of HMs may be appropriate in this case since time is of essence, the aim being to hit the launch site before the enemy missile is launched.

4.4 Discussions

This section positioned, in a very general manner, the potential military utilities of HMs within the CF context, using the DPS and past experiences. It is suggested that the military applications envisioned for HMs may play an important role in the future, especially in the context of international security, including major coalition and counter-terrorism campaigns. Although not as obvious for the Canadian and North American Defence contexts, it appears that TST engagement, one of the potential roles of HMs, may also be important to protect against maritime threats.

It is important to note that the operations in which the CF may participate in the future, and where the previously identified HMs roles may be of great value, all involve more than one country, either as part of a major coalition (NATO) or bilaterally with the US. At this time, the CF mostly relies on other nations to provide these capabilities. In addition, these roles are all performed using other options, for instance, a system of systems involving UAVs and strike aircraft for TST engagement. This leads to some very difficult questions:

- In the future, will the CF continue to rely on other nations to provide some of the HM roles, in particular, the engagement of mobile TST capability?

- Is it worthwhile for the CF and the Government of Canada to invest money in research and development initiatives on hypersonic technologies?

- Will HMs be a better option than the existing options to perform these roles?

The first and the second questions are strategic and should be tackled at a higher level. They involve many considerations such as the frequency for the requirement of such specific missions involving HMs, a cost/benefit analysis, and much more. Such analysis and reflections are not part of this study. The third question is partly answered in the next section, which presents a quantitative analysis of the effectiveness of using HMs in TST engagement.

5. Effectiveness of HMs in the Mobile Time-Sensitive Targets Engagement Cycle

A series of TST examples were presented in Tables 2 and 3 of Section 3. Perhaps the most familiar TSTs are theatre ballistic missile TELs. The purpose of this section is to quantify the potential use of HMs in engagement of TELs. The author acknowledges that the hunt for TELs or such mobile vehicles may not be the most likely type of application that the CF will be asked to conduct in the future. The reason why this type of engagement was chosen over other mobile TSTs is that there is data available that can be used for comparison. Indeed, the hunt for Iraq's Scud ballistic missiles and for TEL engagement during the First Gulf War has been well documented [40,41]. The idea is to show how a high-speed weapon system can improve the overall TST engagement. The logic is that if HMs improve this type of engagement because of their high speed and their other advantages, they will also enhance the engagement of other mobile TSTs such as terrorists fleeing in a vehicle, or high-value military cargo.

5.1 Baseline Scenario

5.1.1 Transporter-Erector-Launchers

A TEL is a vehicle which carries one or more missiles (surface-to-air or surface-to-surface) and is able to elevate the missile into a firing position and launch it without having to remove the missile from the vehicle [42]. In general, they can be detected while they are moving; in their hides, they are relatively invulnerable and almost undetectable. Once the target is detected, a friendly weapon system must engage it before it returns to its hide.

TELs are capable of moving quickly from hidden sites, firing, then hiding again before an air attack can be mounted. Mobile missile TELs represent one of the most demanding time-sensitive targets on the modern battlefield. TELs are highly mobile, relatively autonomous, and produce a low discriminating signature prior to launch. It is very difficult to locate and identify TELs while they are hidden or moving into launch positions, but intelligence, surveillance, and reconnaissance systems have a reasonably good chance of detecting TELs on the battlefield just after launch. This window of opportunity, where the TELs are stationary, may exist for only three to five minutes. Therefore, success requires an end-to-end battlefield operational concept that permits the warfighter to move rapidly from detection and identification, through appropriate battle management at a command and control center, to the assignment of an appropriate attack system, and finally successful engagement and attack.

5.1.2 First Gulf War – TELs and Scud Missiles

Within hours of the first coalition air attacks, Iraq initiated launches against Israel on the afternoon of 17 January 1991. These launches revealed the true Scud threat, i.e.

mobile launchers capable of moving quickly from hidden sites, firing and then hiding again before an air attack can be mounted. Before the end of the war at least 88 missiles were launched at Israel, Saudi Arabia, and Bahrain. Figure 4 shows the number of Scuds fired on the 43 days of the conflict. The types of Scud missiles used were Al-Husayan and Al-Hijarah missiles, whose range can be up to 600 km. Post-war analysis placed the number of TELs at 36, information confirmed in the Gulf War Air Power Survey.

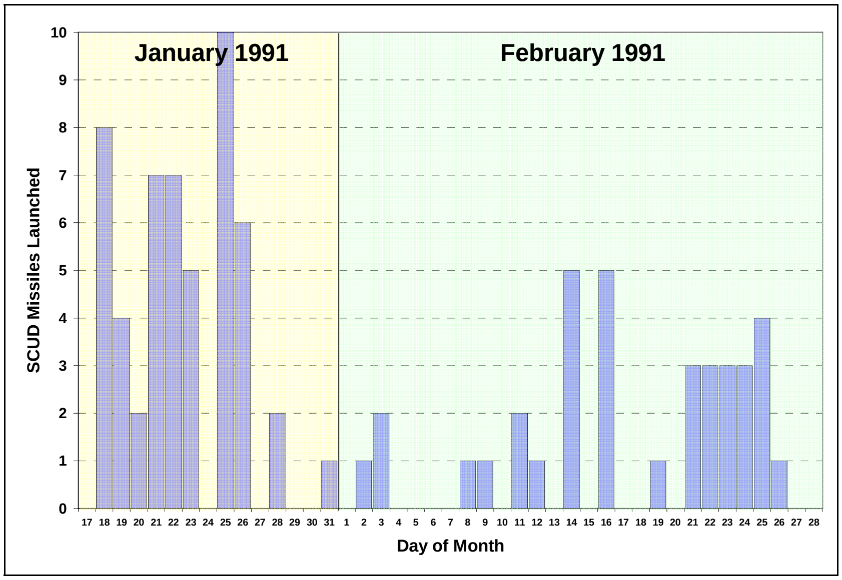

Figure 4: *First Gulf War – Scud Fired by Day*

Reports indicate that the Scud launches caused 42 deaths, 450 casualties, and destroyed or damaged some 10,750 structures [41]. From the outset of the conflict, considering the small number of deaths, Iraq's missiles were judged to be more of a psychological than a military threat. However, the mere fact that the missiles might be carrying chemical or biological warheads represented a big threat to the Coalition, the Israeli and Saudi leaders. Despite the fact that US military officers often repeated that Scuds were a militarily insignificant threat, it remains that the single greatest loss of life in the entire conflict were Scud attacks.

5.1.3 Coalition's Response to TELs

During the course of Desert Storm, the Coalition scheduled and flew 1460 strikes against Scud-related targets, including 50 percent directed against fixed launching sites or other structures (aircraft shelters, overpasses, etc.) suspected of hiding TELs, and 15 percent conducted against exposed TELs [43]. However, there is no technical evidence that a single TEL was actually destroyed by air or special forces attack during the war [41].

Over 80 percent of the Scud launches occurred at night. Poor weather conditions and Iraqi deception techniques made it extremely difficult for coalition forces to detect and attack the dispersed TELs before they launched their missiles. Instead, air commanders focused on destroying the vehicles after they had launched their Scuds [44]. The Coalition hoped that keeping aircraft on station over certain areas would allow strike aircraft to hit the TELs after they had launched their weapons but before they had time to flee to safety.

The signature of the Iraqi Scud missiles proved to be the principal means of launch detection during the conflict. It has been reported that the Defense Support Program (DSP) satellites successfully detected all 88 Scud launches during that conflict [45]. Despite that, no TELs were destroyed during the conflict. The process of dealing with TELs was the following. First, fairly precise coordinates of where the Scud launch occurred were transmitted to the command centre. Then, a decision would be made to decide to engage the TEL or not. In the affirmative, the order was given to the nearest strike aircraft to fly to the launch position, find and track and/or destroy the TEL. However, the results were disappointing. The problem was that by the time coalition aircraft arrived to the launch position, the TEL had invariably moved, and in some cases, was already in a hidden spot. Aircrews complained that if they did not see the launch themselves, they had little chance of finding the TEL [46].

There are many reasons why the hunt for TELs was not successful during the conflict. The technology available at the time allowed the Coalition to detect the launch (using DPS for instance) and also to track targets (in this case TEL) long enough to recognize them as hostile. However, the technology, given the Iraqi’s tactics (cover of darkness or poor weather to mask employment), could not assure tracking beyond that point (when the launch was detected). Such situations required the ability to strike targets within minutes, which was not possible with the strike aircraft (flying only at approximately Mach 0.8). To compensate for the lack of speed, the aforementioned strategy used by the Coalition might have been more efficient if many aircraft (more than what was used during the conflict) would have been on-station simultaneously. The question of how many aircraft would be required will be addressed later in this section.

5.2 Concept of TEL Engagement Involving HMs

Before introducing the concept of operations that will be studied in this section, consider the typical TEL operation cycle as presented in Figure 5. In the "hide" phase, the TEL is generally in a spot where it is extremely difficult to be detected such as under a bridge, under a highway overpass, in a mine, in a culvert or in some other concealed location. Then, the TEL moves to a pre-surveyed site where the launch will occur. The operating phase includes setting up equipment for the launch, the actual launch and getting ready for departure. Once the operating phase is completed, the TEL moves off as quickly as possible to a hidden spot. It is believed that the whole cycle normally takes between 60 and 90 minutes.

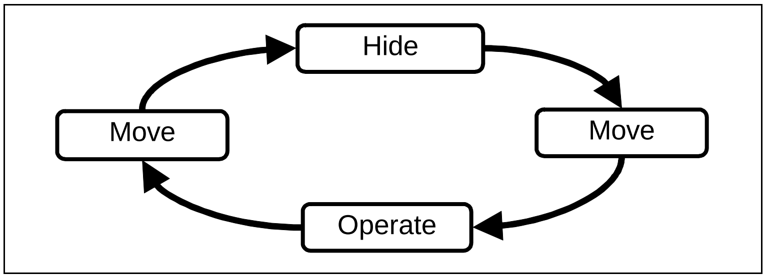

Figure 5: *Typical TEL Operation Cycle*

Considering the fact that a TEL produces a non-existent or a very low signature prior to launch, it is almost impossible to destroy it during that time.

For this reason, the author focussed on post-launch counterforce corresponding to an engagement of the target from the time the Scud is launched until the TEL is back to a hidden location. As opposed to pre-launch engagement, in a post-launch engagement, the game starts with a very observable event – an airborne sensor cue obtained from the launch of a Scud missile.

The concept of engagement proposed and analyzed in this section is very similar to the one introduced in [37]. After the Scud is launched, a signature is detected either from satellites (like DSP), from an Unmanned Air Vehicle (UAV), or any other airborne sensor. The coordinates of the launch position are passed to the command centre which then decide to engage or not the target. If the decision is positive, the order is given to send the HM to the location of the launch (or where the TEL was last spotted). Once at the launch position, the HM delivers a sub-munition which searches the area, trying to find, identify and attack (if ever found) the moving TEL.

It is very likely that the TEL will move during the HM’s flight time. Evidently, the sooner the HM reaches the launch location the better are the chances that the TEL will be found (see Figure 2) and eventually destroyed. Ideally, if the HM gets to the launch location before the TEL starts to move, it is almost guaranteed that the TEL will at least be hit. Although this is a very unlikely situation, it has more chance to occur when high-speed weapon systems such as HMs are used compared to regular strike aircraft.

5.3 Methodology

A Monte Carlo simulation, which will be described later, was developed to quantify the effectiveness of the concept of operations introduced earlier to engage mobile TSTs, in particular TELs.

5.3.1 Assumptions

The following assumptions were made:

- Baseline Case Study: The author decided to reproduce the hunt for TELs that happened during the 43 days of the First Gulf War. The aim was to prevent Scud missile attacks from Iraq (launched from mobile vehicles such as TELs) at Israel, Saudi Arabia, and Bahrain. Figure 6 contains a map of Iraq where the shaded area corresponds to potential Scud launch sites that, if used, can reach one of the three countries. This area may seem quite large, but at the beginning of the conflict, the Coalition did not know where the mobile launchers would operate. This area got smaller as the conflict evolved, as information based on previous launches allowed for a better appreciation of the area of operations.

Figure 6: *Map of Iraq and Potential Launch Area*

- Frequency and Distribution of Scud Launches: The distribution of the Scud launches follows the probability distribution presented in Figure 7, which was obtained from the data displayed in Figure 4. The expected number of Scud launches is 2.05 per day. It is assumed that all Scuds will be fired from mobile launchers and not from fixed launch sites. Additionally, it is assumed that two different Scud launches on a given day come from different enemy vehicles.

- Cue (Launch Signature Detection): The probability of cue is assumed to be 90 percent. This percentage is pessimistic since in reality, 100 percent of all the 88 Scud launches were detected by the DSP [45] during the First Gulf War.

The cue delay, i.e. the time to transmit the information to the command center, was fixed to 3 minutes. The same value was used in previous studies [47].

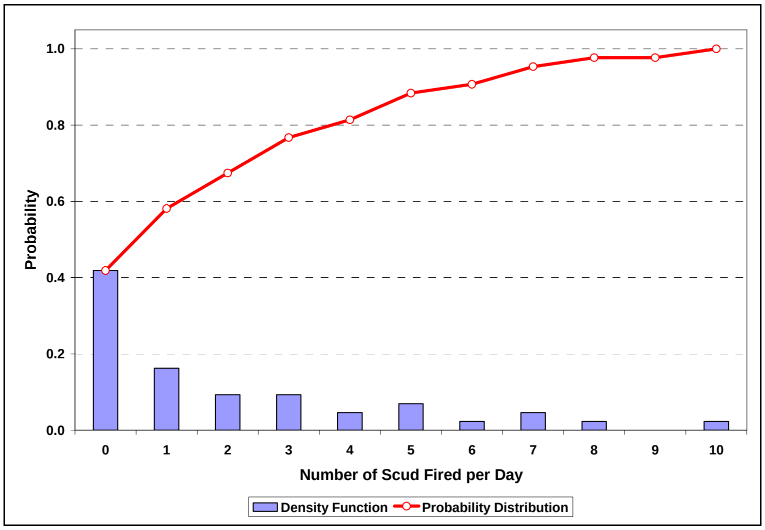

Figure 7: *Probability Distribution – Scud Missiles Fired per Day*

- Sub-Munition: It was assumed that each HM is loaded with a sub-munition of type Low Cost Autonomous Attack System (LOCAAS). The LOCAAS is a one time-use folding-wing air-launched miniature cruise missile that can be deployed from aircraft, UAVs, missiles, or munition canisters [37]. It is envisioned as a miniature, autonomously powered munition capable of broad area search, identification, and destruction of a range of mobile ground targets. It has an effective search rate of 1.67 km^2/min and can cruise for up to 30 minutes.

- TELs: Once the TEL launches the missile, it is assumed that it can move in any direction, 5 minutes after the launch, at constant speed of 25 km/h. The time it takes for the TEL to move off to its hidden spot follows a triangular distribution with maximum of 30 minutes, minimum of 20 minutes and mode of 25 minutes.

- HM System: The HM is capable of flying at a speed of Mach 6 (7242 km/h). It is launched from a fixed site, located outside of Iraq, at a maximum range of 1000 km. The maximum range and the speed of the HM will also be varied in the simulations for sensitivity analysis. As mentioned previously, the HM is capable of carrying and delivering one LOCAAS.

- Identification and Kill Probabilities: The probability of the LOCAAS to identify the target was set to 0.90. The probability of kill once found and identified was also assumed to be 0.90. In the absence of operational data, these numbers seemed reasonable as they were used in similar studies [47].

5.3.2 Monte Carlo Simulation

A Monte Carlo simulation was built in Visual Basic Application for Excel. In the model, targets, representing Scud missiles launched from TEL, are generated with the probability distribution shown in Figure 7. Note that the probability distribution is not hardcoded or fixed in the model. The user can change it depending on the scenario of interest.

The Scud launch locations are uniformly distributed in the area of interest specified by the user (for instance, see map of Iraq in Figure 6). At the time the target is generated, the model draws a random variable to determine if the launch is detected by the airborne sensors, based on the probability of cue. If the launch is detected, the model simulates the movement of the TEL and the HM missile launch in the direction of the position of the Scud launch.

Once at the launch location, the HM delivers the sub-munition, which then performs the search. The logic used for the search process is stochastic and depends on the speed of the TEL, the time it takes for the weapon system (in this example, the HM) before it delivers the sub-munition and the effective search rate of the sub-munition. For each time step, the sub-munition has a probability of finding the TEL corresponding to the ratio between the searched area over the potential area where the target could be located. The search process implemented in the simulation is described in detail in [48].

If the sub-munition finds the TEL before it has moved to a hidden spot, another random variable is drawn to determine if the TEL has been identified. In the affirmative, meaning that the sub-munition can engage the target, the model generates another random variable to decide if the TEL is destroyed of not.

The user specifies the duration of the simulation, in days, as well as the number of runs (or replications) to be accomplished. Various statistics are compiled in order to quantify the effectiveness of the counterforce measures taken.

5.4 Scenario Analysis

5.4.1 Number of TELs Destroyed

The first question that was addressed using the model is how many TELs the Coalition could have expected to destroy during the First Gulf War if they had used the HM concept of engagement introduced earlier. Obviously, this varies significantly depending on the location of the HM launch sites. During the conflict, Coalition troops were deployed to various locations. The HM launch sites should be selected such that they are relatively well protected and available from the beginning of the conflict. For the purpose of this analysis, the two launch sites presented in Table 5 were considered. The locations of the two sites are also represented graphically by the red squares in Figure 8.

Table 5: HM Launch Sites

Site	Base	Location
A	Prince Sultan Air Base	Al Kharj, Saudi Arabia
B	Incirlik Air Base	Adana, Turkey

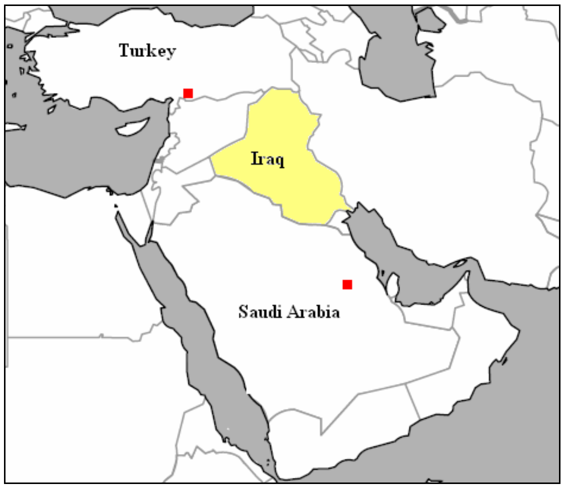

Figure 8: *Selected Hypersonic Missiles Launch Sites*

Three different launch site scenarios were considered: the first scenario with only Site A (Saudi Arabia), the second one with only Site B (Turkey) and the third one, with both sites (A and B) active at the same time. In the Monte Carlo simulation, if there are multiple sites, the closest HM launch site from the location of Scud launches is used. The maximum range of the HM used in the simulation was set to 1000 km.

A total of 500 runs for each configuration were executed with the model and the average total number of TELs left as a function of time was computed. It was assumed that the initial TEL fleet was 50.

Figure 9 shows the results obtained for the three scenarios. Approximately two Scuds per day were launched for all three scenarios. An average of 13, 27 and 30 TELs were destroyed respectively for Scenario 1 (Site A), Scenario 2 (Site B) and Scenario 3 (Sites A and B).

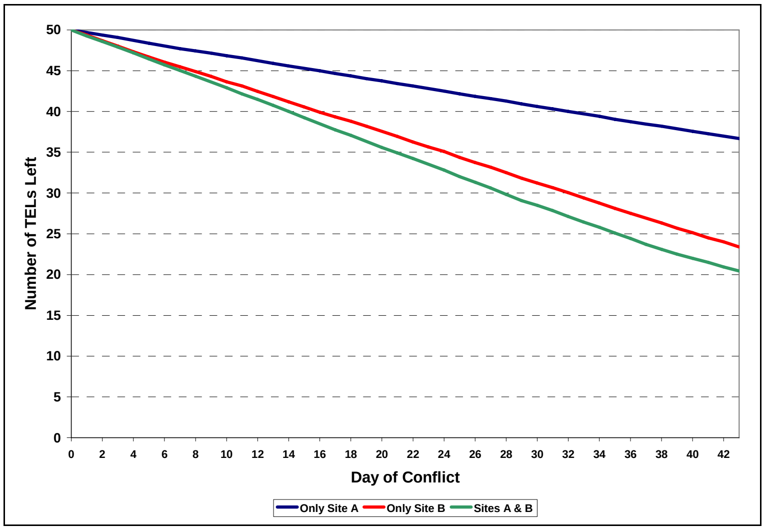

Figure 9: *Number of TELs Left as a Function of the Day of Conflict*

In the scenario where the launch site is located in Al-Kharj, Saudi Arabia (Scenario 1), the probability of TEL destruction was approximately 0.145. This result was obtained because of the maximum range of the HM (1000 km), which only allowed protection of the southeast portion of Iraq. In Scenario 2, launch site at Adana, Turkey, the probability went up to approximately 0.310. In this case, the launch site allowed, again because of the range limitation, coverage of the northwest part of Iraq. This probability was higher than for Scenario 1 simply because Adana is closer to the area of interest than Al-Kharj. Obviously, in the third scenario where both sites were utilized, the probability increased to approximately 0.353. In this case, both the North and the South parts were protected, either by Site A or Site B. The improvement between Scenarios 2 and 3 is not significant, representing only three more TELs destroyed at the end of the conflict.

5.4.2 Probability of TEL Destruction versus Maximum Range

A second question that is worthwhile asking is how the range of the HMs influenced the probability of destroying the TELs. To answer this question, the same three baseline scenarios were used. In this case, the three scenarios were executed by varying the range of the HMs. Four values of range were employed: 600 km, 800 km, 1000 km and 1200 km. The model was executed 5000 times for each combination (Scenario/Range) and the probability of TEL destruction was calculated. The results are shown in Figure 10.

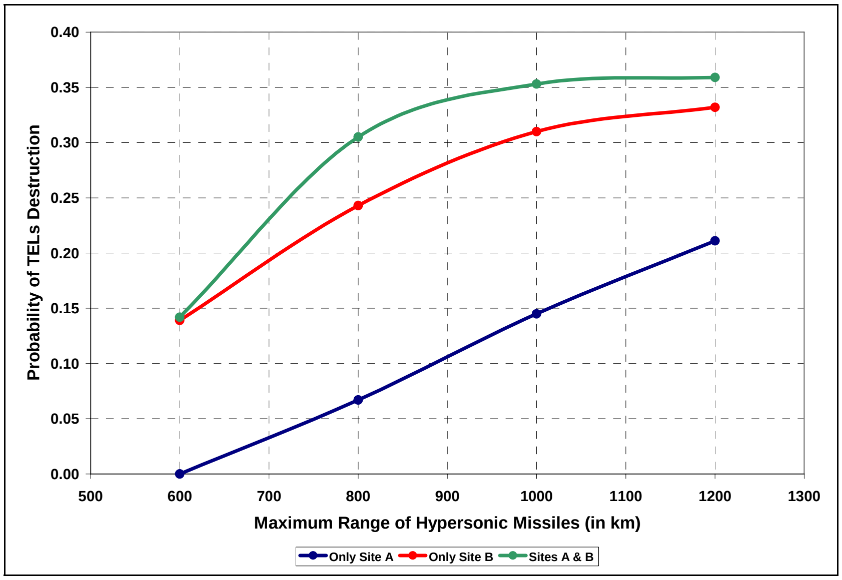

Figure 10: *Probability of TELs Destruction as a Function of the Maximum Range of the HM*

Evidently, the range has a significant impact on the efficiency of the HM to destroy the target. For instance, the results for Scenario 1 (launch site in Saudi Arabia) show that if the range is not at least 600 km, the launch site is useless (probability equals 0). This can be explained by the fact the distance between Site A and the area of interest (in this case Iraq) is more than 600 km. The results obtained in Scenario 2 are better than for Scenario 1 because Incirlik Air Base is closer to Iraq than is Prince Sultan Air Base.

Based on the results of Scenario 3 (Sites A and B), it appears that a maximum range of 1000 km should be enough. At that point, it seems like increasing the range of the HM would not have a significant impact. In fact, augmenting the range from 1000 km to 1200 km only improves the destruction rate by 0.006 (0.353 versus 0.359). The reason is that with a maximum range of 1000 km, the two launch sites can practically cover the whole area of interest. Obviously, the shorter the range, the bigger the unprotected area in the middle of Iraq, and therefore, the lower the probability of TEL destruction.

5.4.3 Probability of TEL Destruction versus HM Speed

Another variable is the speed of the HMs. Up to now, the speed that was used in the analysis was Mach 6. But what happens if the speed varies? The Monte Carlo simulation was again used to answer this question. The baseline scenario that was used is the one with two launch sites (A and B) and the range of the HM was set to 1000 km. A total of 5000 runs were executed with the model for each of the following speeds: Mach 5, 6, 7, and 8. In each case, the probability of TEL destruction was estimated. The results are depicted in Figure 11.

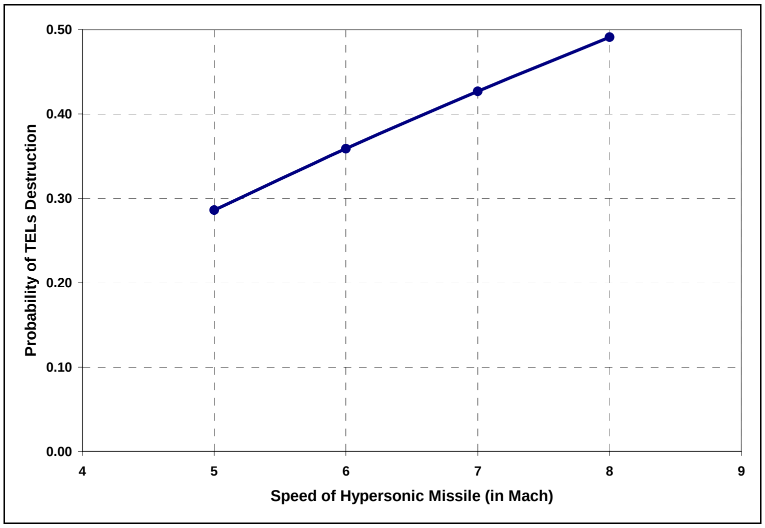

Figure 11: *Probability of TELs Destruction versus Speed of HM – Maximum Range 1000 km, Two Launch Sites*

As expected, as the speed of the HM increases, the probability of TEL destruction increases at the same time. At Mach 8, the model predicts that almost 50 percent of the TELs would be destroyed, which corresponds to an improvement of 0.205 compared to a speed of Mach 5. This is relatively significant in such a conflict, since it represents approximately 18 more TELs destroyed at the end of the 43 days (assuming an average of two Scud launches per day).

5.4.4 Number of Strike Aircraft

It was mentioned earlier that the Coalition had no success with TEL engagement during the First Gulf War. To do a fair comparison, it should be assumed that the strike aircraft would be equipped with the same sub-munition (i.e. LOCAAS) as the HM in the previous analysis. The question can be reformulated as follows: How many strike aircraft (loaded with LOCAAS) would be required to obtain a probability of TEL destruction of 40 percent? This percentage represents the probability envisioned for TEL destruction if the Coalition had used the strategy employing HMs, with a range of 1000 km and a speed between Mach 6 and 7.

The Monte Carlo simulation presented in subsection 5.3.2 was also used to answer this question. The same assumptions (area of interest, cue/identification/kill probabilities, search process, etc.) were made except that the weapons systems were not HMs located outside the area of interest, but rather on-station strike aircraft flying over Iraq.

The number of aircraft was set to 1 and it was positioned in the middle of the area of interest. A total of 5000 runs were made and the probability of TELs destruction was calculated. As long as the probability was less than 0.40, aircraft were added one by one[9] until the probability was greater than or equal to 0.40. Figure 12 shows the results for 0 to 6 aircraft. The 0.40 mark was passed with 6 aircraft. Figure 13 indicates the location of the 6 aircraft. With such a configuration, i.e. 6 on-station aircraft, the model predicts that approximately 40.4% of the TELs would be destroyed.

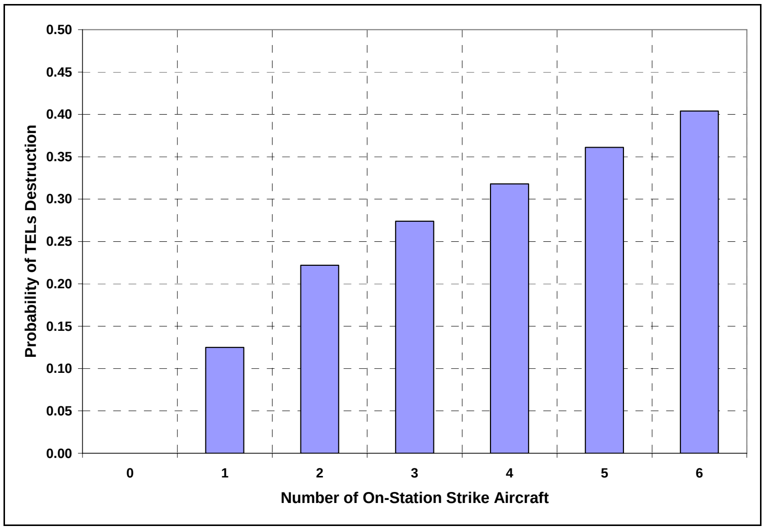

Figure 12: *Probability of TELs Destruction versus Number of On-Station Aircraft*

Six aircraft may not seem a lot. However, in reality, the number of aircraft necessary to support 24 hours, 7 days per week coverage is probably 24, if a 4:1 ratio is used. Another negative aspect is the significant manpower requirement (pilots and aircraft maintainers), which is not as much of an issue with the HM options. Finally, it is worth noting the limited payload of the aircraft (probably 2 or 4 LOCAAS), which could increase the demand for aircraft to keep six aircraft on-station.

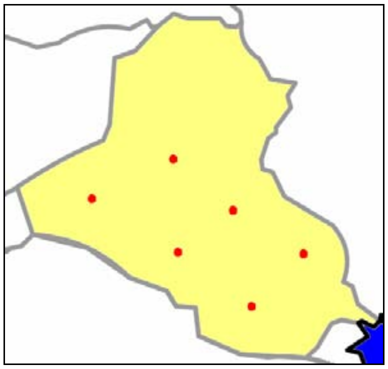

Figure 13: *Location of the Six Strike Aircraft Equipped with LOCAAS*

[9] Note that every time an aircraft was added, the positions of the aircraft were re-determined in order to cover uniformly the area of interest. The positions chosen are not necessarily optimal, but they represent good estimates.

5.5 Discussion

The important assumption made in this section was that the Coalition did not have the ability to continuously track targets for hours or perhaps days, allowing the targets to be recognized and destroyed at leisure. If that was not the case, subsonic aircraft and weapons could be launched from bases many hundreds of kilometres away and be effective.

The success of HMs to engage mobile TSTs such as TELs resides in the fact that HMs can reach quickly the launch site, which allows earlier searching, thereby increasing the chance of finding and eventually destroying the moving targets. The reader should not pay too much attention to the absolute probability values obtained in the scenarios. The estimated probabilities in the 0.30-0.40 range should actually be seen as improvements compared to tactics employed in previous conflicts. These numbers illustrate that high-speed weapon systems have a clear potential in the engagement of moving targets.

Obviously, the two launch sites used were arbitrarily selected amongst the bases where the Coalition troops were deployed during the conflict. In reality a more thorough analysis should be done before the conflict to optimize the location of the HM launch sites in order to maximize the likelihood of destroying the TELs in the area of interest. Note that the results are valid only for this particular scenario. However, one might assume that in a similar situation, i.e. engagement of TELs after Scud launched from country with a size comparable to Iraq, similar performance results could be expected.

Only post-launch engagement was considered in this section. It would be of value to add pre-launch engagement involving HMs, assuming that the sensor technologies were available to detect vehicles such as TELs while moving, to determine how it would affect the overall probability of TEL destruction.

6. Conclusion

This document summarized the OR support provided by the DRDC Valcartier OR Team to the CEFHAW project. One of the mains goals of this report was to provide information and tools for the reader to establish their own assessment of HM utility. The report serves as a starting point for the OR support for the CEFHAW project.

Considering the advantages of HMs (speed, range, survivability, etc.), the main potential applications envisioned for the HMs are the engagement of TSTs (both mobile and fixed or stationary surface targets), attacking HDBTs, SEAD and to serve as an additional defensive layer for an air defence system. It is important to realize that for these applications, HM is not the only technology necessary. All of the potential applications require an integrated system of technologies and different concepts of operations than currently exist. For TST engagement, improved sensors for detection and tracking capabilities, information passing and processing technologies and automatic target recognition capability are all technologies that will have to be enhanced for HMs to be part of the TST engagement solution.

The analysis suggests that the military applications envisioned for HMs may play an important role in the future, especially in the international security context, including major coalition and counter-terrorism campaigns. Although not as obvious for the Canadian and North American Defence contexts, it appears that TST engagement, one of the potential roles of HMs, may also be important to protect against maritime threats. One of the questions asked by the project team was to identify some detailed scenarios where HMs would be of value. The generic scenarios presented in this report can serve as a starting point for the development of more precise and specific scenarios involving HMs to be used in the performance analysis conducted by the members of CEFHAW.

The document also presents a quantitative analysis of the effectiveness of HMs in the engagement of mobile TSTs. The scenario of the hunt for TEL vehicles during the First Gulf War was used as a case study. The analysis clearly shows that HMs can be of great value for such engagements. Considering two HM launch sites and assuming a maximum range of 1000 km and a speed between Mach 6 and 7, the probability of TEL destruction was estimated to be 0.40. The author suggests that in the future, similar studies should be conducted with more accurate data, such as range and speed of HMs, probabilities of identification and kill of LOCAAS (or other subsystem), and more. In addition, only one particular scenario was considered in this work; it would also be worthwhile to do similar quantitative analysis using different scenarios, such as a scenario involving protection against maritime threats using HMs. The only other option considered in this report was strike aircraft; maybe more work should be done to compare HMs with other options such as UAVs equipped with weapons for TST engagement.

Although the main objectives of the study were fulfilled, the report did not answer a very fundamental question: Is it worthwhile for the CF and the Government of Canada to invest money in research and development initiatives on hypersonic technologies? This is a very difficult question to answer even though it is clear that long-range HMs may be one of the transformational capabilities that military forces could use. Many aspects would have to be considered, for instance the fact that the operations in which the CF may participate in the future, and where the previously identified HM roles may be of great value, all involve more than one country, either as part of a major coalition (NATO) or bilaterally with the US. Additionally, at this time, the CF mostly relies on other nations to provide some of the HM roles, in particular, the engagement of mobile TST capability. This question would have to be tackled at a higher level, i.e. from a strategic and a political point of view. Such analysis and reflections could be the subject of a whole study.

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List of Symbols/Abbreviations/Acronyms

ARRMD	Affordable Rapid Response Missile Demonstrator
CA	Canadian
CEFHAW	Capability Engineering for Hypersonic Airbreathing Weapons
CF	Canadian Forces
CDS	Chief of Defence Staff
CAT	CDS Action Team
CORA	Centre for Operational Research and Analysis
DARPA	Defense Advanced Research Projects Agency
DND	Department of National Defence
DPS	Defence Planning Statement
DRDC	Defence Research and Development Canada
DSP	Defense Support Program
F	Fahrenheit
FPS	Force Planning Scenario
HDBT	Hardened or Deeply Buried Target
HM	Hypersonic missile
IADS	Integrated Air Defence System
LOCAAS	Low Cost Autonomous Attack System
MH	Missile Hypersonique
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization

nm	Nautical Niles
OR	Operational Research
TCT	Time Critical Target
UAV	Unmanned Air Vehicle
US	United States
UN	United Nations

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This document summarizes the Operational Research (OR) support provided by the Defence Research and Development Canada – Valcartier OR group to the Capability Engineering for Hypersonic Airbreathing Weapons project. The main objective of the OR study was to examine the military utility of long-range hypersonic missiles (HMs). Firstly, the author presents an historical background on HMs development, the critical technology challenges that HMs are facing, and the main advantages of HMs. Secondly, an overview of the potential military utilities and applications of HMs is included. The potential applications and contributions of HMs are put into context, in a general manner, within the current environment and requirements of the CF, which is dictated by the Defence Policy Statement and the eleven Force Planning Scenarios. Finally, the author includes a quantitative analysis on the effectiveness of HMs to engage mobile time-sensitive targets. The hunt for transporter-erector-launcher vehicles during the First Gulf War is used as case study. The results of the analysis showed that HMs can be of great value in the engagement of time-sensitive targets.

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Hypersonic
Hypervelocity
Missile
Time-Sensitive
Time-Critical
Target
Military Utility
Hard Deeply Buried Target
Monte Carlo
Simulation