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# Simulation, integration and optimization of technologies for HEMi

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**Defence R&D Canada – Valcartier**

Technical Report

DRDC Valcartier TR 2006-636

March 2007

Canada



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**Defence R&D Canada – Valcartier**

Technical Report  
DRDC Valcartier TR 2006-636  
March 2007

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This work has been carried out between April 2001 and March 2006 under the High Energy Missile (HEMi) Technology Demonstration Project.

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## Abstract

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The capabilities of the HEMi compact hypervelocity kinetic energy missile technologies were integrated using modelling and simulation to provide overall missile system performance including kill probability, velocity at the target, flight velocity profile, accuracy, size, mass, launch environment, etc. To achieve this task efficiently, tools were developed for the management of simulation parameter sets, subsystem models, documentation and automatic generation of reports on simulation results. A preliminary concept definition study was performed during the project definition phase. The objective of this study was to verify the feasibility of achieving the mass-speed-distance specification with five different airframe/thrust management configurations. Then, a series of parametric studies were done to determine the most appropriate booster shape to achieve the kinematic objective within the stated mass and length constraints. To expedite the HEMi concept refinement process, an effort was made to integrate in a single architecture many of the engineering analysis codes used to analyze and define the model parameter sets of HEMi. The integration of the analysis codes permitted the interdependent variables to be linked, thereby allowing multidisciplinary analysis and optimization of the HEMi concept. The performance of the latest version of HEMi was analyzed through engagement modelling and simulation.

## Résumé

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Les possibilités des technologies du missile hypervélocité compact à énergie cinétique HEMi ont été intégrées en modélisation et simulation pour fournir les performances globales du système comprenant la probabilité de destruction, la vitesse à la cible, le profil de vitesse de vol, la précision, la taille, la masse, l'environnement de lancement, etc. Pour réaliser cela efficacement, des outils pour la gestion des ensembles de paramètres de simulation, des modèles de sous-systèmes, de la documentation, et de productions automatiques des résultats de simulation ont été développés. Une étude préliminaire de définition de concept a été réalisée pendant la phase de définition de projet. L'objectif de cette étude était de vérifier la possibilité de réaliser les spécifications de masse-vitesse-distance pour cinq combinaisons différentes de fuselages et de profils de poussée. Puis, une série d'études paramétriques a été exécutée pour évaluer la forme de propulseur la plus appropriée pour atteindre l'objectif de cinématique dans les contraintes permises de masse et de longueur. Afin d'augmenter le rythme du processus d'amélioration de concept de HEMi, un effort a été fait pour intégrer dans une seule architecture plusieurs des codes d'analyse des technologies utilisés pour l'analyse et la définition des ensembles de paramètres du modèle de HEMi. L'intégration des codes d'analyse a permis de relier les variables interdépendantes, rendant possible l'analyse multidisciplinaire et l'optimisation du concept HEMi. L'analyse de la performance de la dernière version de HEMi a été exécutée en utilisant cette modélisation et simulation de l'engagement.

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## Executive summary

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### Simulation, integration and optimization of technologies for HEMi

**R. Lestage, M. Lauzon; DRDC Valcartier TR 2006-636; Defence R&D Canada – Valcartier; February 2007.**

The High Energy Missile Technology Demonstrator (HEMi TD) is a project to demonstrate the lethality of a compact hypervelocity kinetic energy missile with a view to providing light armoured vehicles with sufficient lethality to destroy a main battle tank. Modelling and simulation (M&S) played an important role in assessing the performance of the individual technologies in a system context, where the performance of the missile was evaluated against the performance requirements. The results of the performance assessment directed the development of the HEMi technologies.

The capabilities of the HEMi technologies were integrated by M&S to determine overall missile system performance including kill probability, velocity at the target, flight velocity profile, accuracy, size, mass, launch environment, etc. This includes the investigation of design options and trade-off studies. Simulating the evolution of the HEMi concept required the construction and maintenance of several computer models and parameter sets designed to analyze candidate technologies. To achieve this task efficiently, tools were developed for the management of simulation parameter sets, subsystem models, documentation and automatic generation of reports on simulation results.

Achieving the desired kinematic performance (speed-range) within the specified HEMi missile envelope (mass-size) is a formidable technical challenge. A preliminary concept definition study was performed during the project definition phase. The objective of this study was to verify the feasibility of achieving the mass-speed-distance specification with five different airframe/thrust management configurations. Based on this study, it was decided to continue the investigation of the two-stage configurations with a coasting dart. A series of parametric studies were done to determine the most appropriate booster shape to achieve the kinematic objective within the stated mass and length constraints.

To expedite the HEMi concept refinement process, an effort was made to integrate in a single architecture many of the engineering analysis codes used to analyze and define the model parameter sets of HEMi. The integration of the analysis codes permitted the interdependent variables to be linked, thereby allowing multidisciplinary analysis of the HEMi concept. Missile system design requires high levels of integration between disciplines such as aerodynamics, structures, propulsion and controls. These disciplines are interrelated and interdependent, and all ramifications must be fully considered in the analysis of individual systems and the prediction of system responses. This was particularly true for HEMi, since the length, weight and velocity requirements demand state-of-the-art technologies.

The performance of the latest version of HEMi was analyzed through engagement M&S. The missile's nominal kinematic performance was evaluated by means of a nominal simulation using constant disturbances consisting of booster thrust misalignments and dart separation effects. Monte Carlo simulations with randomly generated disturbances were then used to evaluate missile dispersion and probability of hit.

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# Sommaire

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## Simulation, integration and optimization of technologies for HEMi

**R. Lestage, M. Lauzon; DRDC Valcartier TR 2006-636; R & D pour la défense Canada – Valcartier; February 2007.**

Le démonstrateur de technologie HEMi est un projet visant à démontrer la létalité d'un missile hypervélocité compact à énergie cinétique pouvant fournir à un véhicule blindé léger la létalité suffisante pour détruire un char d'assaut. Afin de diriger le développement des équipes de technologie de HEMi, la modélisation et simulation (M&S) joue un rôle important pour évaluer les performances des technologies individuelles dans le contexte de système où la performance du système de missile est évaluée contre spécification de performances.

Les possibilités des technologies de HEMi ont été intégrées en modélisation et simulation pour fournir les performances globales du système comprenant la probabilité de destruction, la vitesse à la cible, le profil de vitesse de vol, la précision, la taille, la masse, l'environnement de lancement, etc. Ceci inclut la recherche sur les options de conception et les études de compromis. La simulation de l'évolution du concept de HEMi a exigé la construction et l'entretien de plusieurs modèles d'ordinateur et ensembles de paramètres pour l'analyse des technologies candidates. Pour réaliser cela efficacement, des outils pour la gestion des ensembles de paramètres de simulation, des modèles de sous-systèmes, de la documentation, et de productions automatiques des résultats de simulation ont été développés.

La réalisation des performances cinématiques souhaitées (vitesse-distance) dans l'enveloppe désirée de missile de HEMi (masse-longueur) représente un défi technique critique. Une étude préliminaire de définition de concept a été réalisée pendant la phase de définition du projet. L'objectif de cette étude était de vérifier la possibilité de réaliser les spécifications de masse-vitesse-distance pour cinq combinaisons différentes de fuselages et de profils de poussée. Sur la base de cette étude, on a décidé de continuer la recherche sur la configuration à deux étages avec dard. Une série d'études paramétriques a été exécutée pour évaluer la forme de propulseur la plus appropriée pour atteindre l'objectif de cinématique dans les contraintes permises de masse et de longueur.

Afin d'augmenter le rythme du processus d'amélioration de concept de HEMi, un effort a été fait pour intégrer dans une seule architecture plusieurs des codes d'analyse des technologies utilisés pour l'analyse et la définition des ensembles de paramètres du modèles de HEMi. L'intégration des codes d'analyse a permis de relier les variables interdépendantes, rendant possible l'analyse multidisciplinaire et l'optimisation de HEMi. La conception de systèmes de missile exige des niveaux élevés d'intégration parmi les disciplines telles que l'aérodynamique, les structures, la propulsion et les commandes. Ces disciplines sont mutuellement interactives et couplées, et on doit tenir compte de tous ces effets dans l'analyse des missiles et la prévision de la réponse du système. Cela est particulièrement vrai pour HEMi, car les spécifications de longueur, de poids et de vitesse exigent des technologies de dernier cri.

L'analyse de l'exécution de la dernière version de HEMi a été effectuée en utilisant la modélisation et simulation de l'engagement. Une simulation nominale employant des perturbations constantes composées de déviations d'alignement de poussée du moteur et des effets de séparation du dard ont

permis l'évaluation de la performance cinématique nominale du missile. Puis, des simulations de type Monte Carlo employant des perturbations aléatoirement produites ont été utilisées pour évaluer la dispersion et la probabilité de frappe du missile.

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# 1. Introduction and objectives

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The High Energy Missile Technology Demonstrator (HEMi TD) [1] is a project to demonstrate the lethality of a compact hypervelocity kinetic energy missile with a view to providing light armoured vehicles with sufficient lethality to destroy a main battle tank.

Modelling and simulation (M&S) played an important role in assessing the performance of the individual technologies in a system context, where the performance of the missile was evaluated against the performance requirements. The results of the performance assessment directed the development of the HEMi technologies.

The capabilities of the HEMi technologies were integrated by M&S to determine overall missile system performance including kill probability, velocity at the target, flight velocity profile, accuracy, size, mass, launch environment, etc. This includes the investigation of design options and trade-off studies such as:

- development of the engagement-level M&S capability;
- model evolution and concept analysis studies;
- component-level and system-level performance and trade-off analyses to support concept development;
- streamlined integration of the evolving component models (guidance, propulsion, etc.) in the engagement model;
- verification and validation at the component and system levels;
- configuration/version control; and
- documentation of model and analysis results (automated report generation).

Since the M&S effort must track an evolving concept, several functionalities needed to be developed and implemented. These functionalities included a library of reusable subsystem models, a system for managing model parameter sets and a process for batch runs, including automated report generation.

In the analysis of the subsystem components, the subsystem models needed to be used in different models either to perform unit tests on the subsystem or to test their integration within the full system. The subsystem model is a parameterized mathematical equation representing a physical entity. To ensure model consistency and version control so that all models use the most recent version of the subsystem model, a library repository of subsystem components had to be used for model construction.

Each of the subsystem models can be configured with different sets of parameter values to adapt the parameterized mathematical equation of the models so that they represent a specific version of a subsystem. This requires the creation and management of different parameter sets, which

should also be version-controlled to ensure consistency between different test models. Scenarios define which combination of subsystem parameters are used for a given simulation.

A batch run allows consecutive simulations of different scenarios and parametric studies, where parameters are varied in sequence from run to run. To efficiently create and easily summarize large sets of simulation results, an automatic report generation procedure needed to be implemented to automatically update system-level and trade-off analysis reports based on updated models.

## 2. Models, parameters and results management tools for simulations

---

The simulation of the evolution of the HEMi concept requires the construction and maintenance of several computer models and parameter sets for analysis of candidate technologies.

To execute this task efficiently, tools for the management of simulation parameter sets and for the documentation of simulation results have been developed [2, 3].

This section gives an overview of these tools.

### 2.1 Libraries for model components management

Libraries allow for an efficient reuse of blocks in different models.

The library is the location where block modifications or improvements are performed. Modifications are then propagated into models which use library components in a linked mode.

For example, as represented in Figure 1, the same block B is used in two different models; one could be for testing the block, the other one for simulation of the block in a missile engagement.

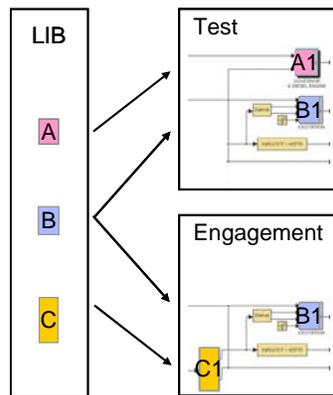


Figure 1: Reuse of model component B in two simulations

Since the block resides in a linked library, this ensures that whenever the library is updated, all models using this library will use the latest version of the library block.

### 2.2 Parameter and scenario management

For each unique block in the library, a library of parameter sets is created. Parameter sets are used to customize the library block to represent a given version of the HEMi concept. In Figure 2, the library block B may use two alternate sets of parameters (B1 or B2).

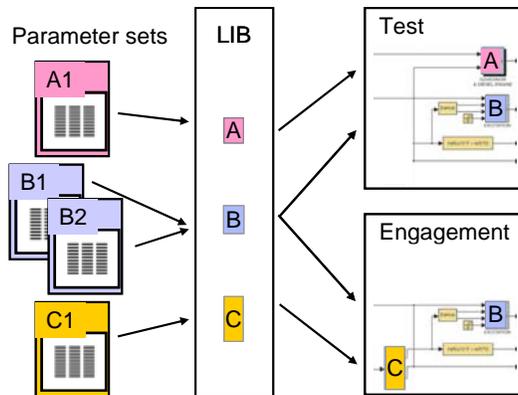


Figure 2: Use of parameter sets to customize models.

Scenario files are used to define which block uses which parameter set, as shown in the next figure.

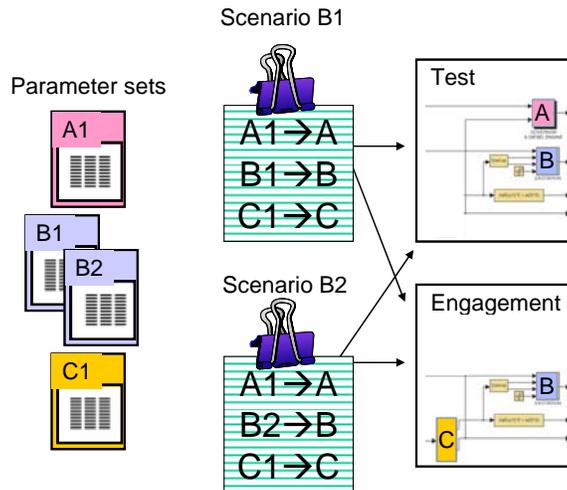


Figure 3: Scenarios B1 and B2 defining which parameter set is used by the model.

## 2.3 Automatic report generation

Since models evolve at the same rate as the HEMi concept, an efficient method to report on the performance of the concept is required. For that purpose, an automated report generation procedure has been developed, so that the simulation results documents can be rapidly updated when improved or updated parameters on the HEMi system become available.

The user creates a report template for the model with a model description and placeholders for the results tables and figures.

Each library block has a sub-report template created with a description and placeholder for the parameters tables and figures.

The automated report generation process dynamically builds the simulation results report based on templates and links result figures and parameter tables.

### 2.3.1 Report generation example

Figure 4 presents a simple model representing a first order polynomial model  $y=mx+b$ .

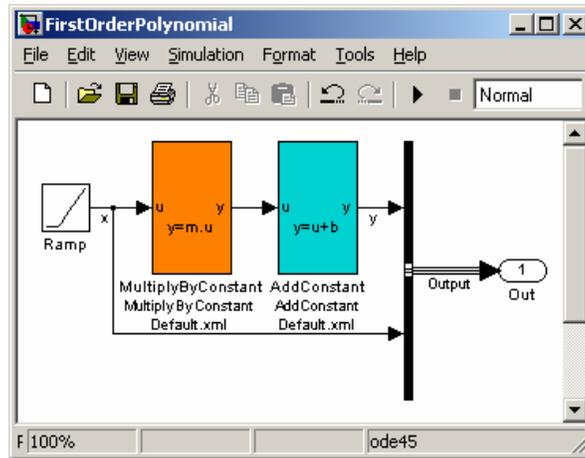


Figure 4: First order polynomial model with two subsystems.

The model is composed of two subsystems, the first that multiplies the input by 'm' and the second that adds 'b'.

Figure 5 presents a report that documents the input-output relationship of the model for the given subsystem parameters 'b' and 'm'. If the values 'b' and 'm' of the model are changed, the report can be regenerated automatically in a matter of seconds to update the figure and the tables.

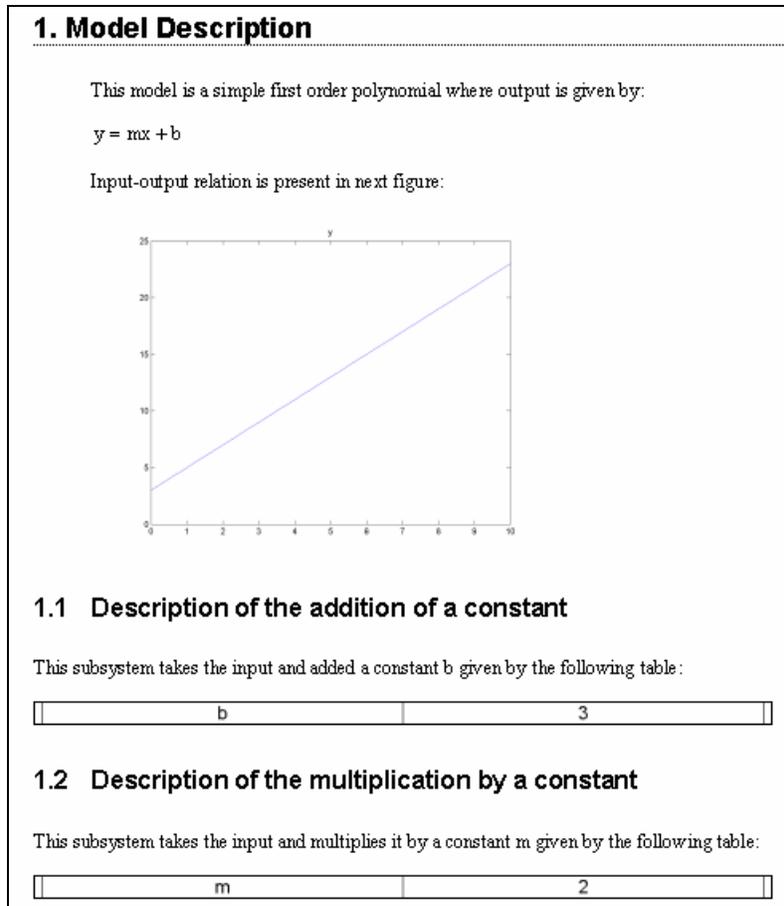


Figure 5: Generated report that presents the input-output relationship of the model for the given subsystem parameters 'b' and 'm'.

## 2.4 Summary of HEMi simulation tools

The methodology to provide for an efficient use of models, parameters and results has been implemented early in the HEMi project.

Figure 7 presents the library of the 11 components of the HEMi concept implemented in Matlab/Simulink [4]. During the development of HEMi, more than 130 parameters sets have been generated for the 11 blocks of the library, and nearly 100 simulation results reports have been generated using this automated report generation methodology. This tool has proven to be very valuable to provide fast, accurate and up-to-date feedback to the HEMi technology teams.

The next sections present simulation results obtained using these tools.

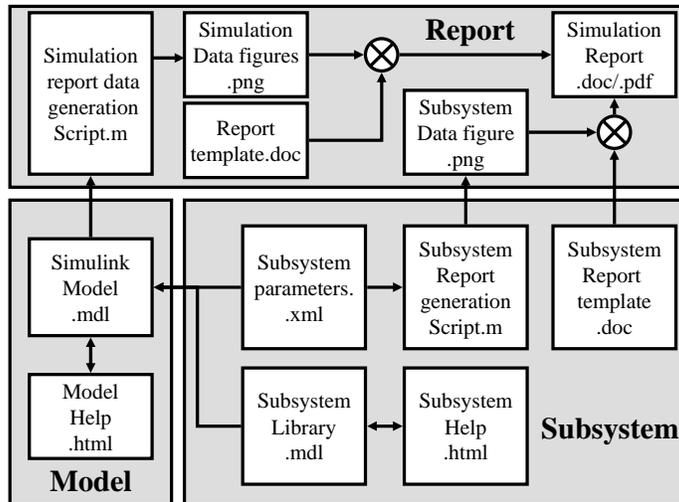


Figure 6: Summary of the HEMi modelling architecture.

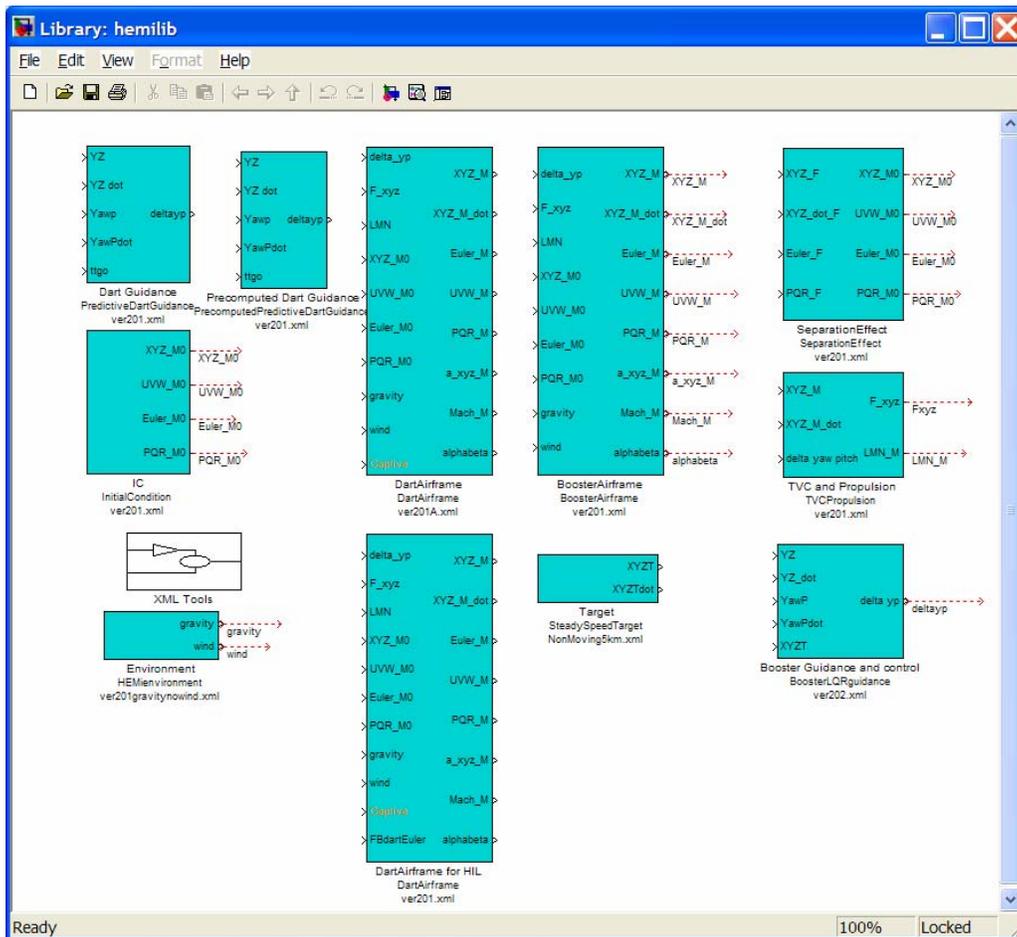


Figure 7: HEMi Simulink model library

### 3. HEMi preliminary concept definition

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Achieving the desired kinematic performance (speed-range) within the desired HEMi missile envelope (mass-size) represents a critical technical challenge. The challenge comes from the fact that a sufficient amount of propellant energy must be stored within the total mass-volume to deliver the required energy at the target. The propellant energy also impacts on the casing, hence on the mass of the overall missile, and on its performance.

A preliminary concept definition study [5] was performed during the project definition phase (FY 00/01). The objective of this study was to verify the feasibility of achieving the mass-speed-distance specification [6] for five different airframe/thrust management configurations. The mass-speed-distance specification used in this study was:

- Penetrator kinetic energy at the target: 10 MJ (this requirement was converted to a penetrator rod having a mass of 4.13 kg and a speed of 2200 m/s (Mach 6.5) at the target);
- Total projectile mass at launch: 22.7 kg;
- Short range capability: 10 MJ delivered at 400 m;
- Long range capability: 10 MJ delivered at 5000 m;

Table 1 shows the five different configurations considered. The configurations 1, 2 and 5 consist of a unitary projectile with a propulsion system having one of three different thrust profiles (boost-coast, boost-sustain, dual-impulse). The other two configurations consist of a two-stage booster/dart with two different thrust profiles (boost-separate-coast, boost-separate-sustain).

Table 1. Airframe/thrust management configurations

<b>Configuration no.</b>	<b>Airframe</b>	<b>Thrust management</b>
<b>1</b>	Unitary	Boost-coast
<b>2</b>	Unitary	Boost-sustain
<b>3</b>	Two-stage	Boost-coasting dart
<b>4</b>	Two-stage	Boost-separate-sustain dart
<b>5</b>	Unitary	Dual-impulse

A parametric study of key design parameters driving the missile kinematic performance was performed to select the most promising configurations. The parameters studied were propellant specific impulse, mass flow rate, drag coefficient and external casing diameter. The algorithm used in this analysis consisted of computing the propellant mass required to achieve the mass-speed-range specification. In many combinations of the design parameter values, it was simply impossible to incorporate the required amount of propellant within a “50 lb” missile to achieve the performance. A one-degree of freedom flyout model coupled to a motor mass sizing loop was used to evaluate the feasibility of the proposed configurations.

### 3.1 Propulsion model

Starting from a user-specified fuel mass flow rate and specific impulse, the propulsion model computes an average thrust over a burn time. The propulsion model assumes in this preliminary study that the motor produces a constant thrust equal to the average thrust during motor operation. The total propellant mass is limited by the total missile mass and the penetrator mass. Propellant specific impulses considered ranged from 220 to 320 s.

### 3.2 Aerodynamic model

Drag is computed from a Mach dependent  $C_d$  coefficient. The nominal  $C_d$  is shown in Figure 8.

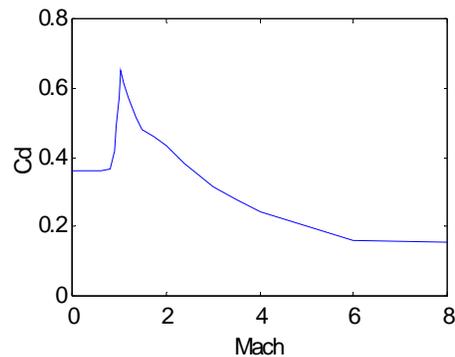


Figure 8: Drag coefficient

The sensitivity of the missile kinematic performance to the drag coefficient has been studied by varying the drag coefficient by +/-25% from the nominal value.

The projectile diameter is taken into account in the computation of the reference area. Diameters of 125, 145 and 165 mm were considered.

### 3.3 Airframe/thrust management configurations

#### 3.3.1 Unitary boost-coast configuration:

This is a single-stage-to-target configuration. A booster accelerates the missile to a maximum speed and then the missile coasts to the target after motor burnout (Figure 9). The simulation of this configuration requires the computation of the propellant mass flow rate to accelerate the missile to 2200 m/s at 400 m. Then the total propellant mass is computed to accelerate the missile to a speed higher than 2200 m/s followed by a deceleration up to the target at 5000 m, with a speed of 2200 m/s at the target. Results show that the kinematic specification cannot be achieved with this configuration, except for the projectile with the lowest  $C_d$  (0.75 of nominal value), the smallest diameter (125 mm) and the propellant with the highest specific impulse (320 s). The penetrator remains within the carrier vehicle.

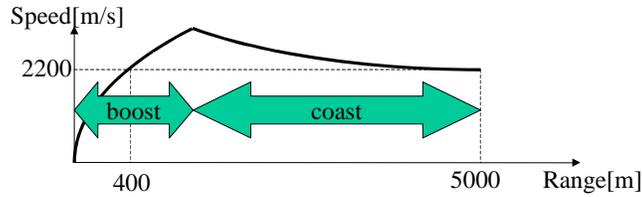


Figure 9: Boost-coast configuration velocity profile

### 3.3.2 Unitary boost-sustain configuration:

A booster with the proper mass and mass flow rate accelerates the missile to 2200 m/s at 400 m. A second propulsion phase (sustainer) maintains the speed up to 5000 m by offsetting the drag force (Figure 10). Maintaining a missile speed of 2200 m/s during the last 4600 m requires a large amount of energy, so an important fraction of the missile mass is composed of propellant. The specification of the total mass at launch (50 lb or 22.7 kg) makes this configuration very difficult to achieve. The penetrator remains within the carrier vehicle.

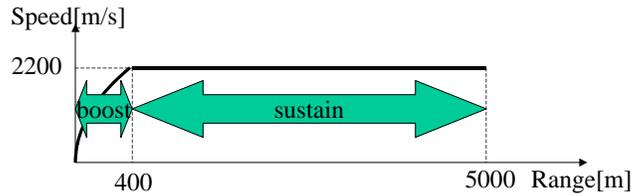


Figure 10: Boost-sustain configuration velocity profile

### 3.3.3 Unitary dual-impulse configuration:

This configuration maintains a relatively low speed during the flight to the target, followed by a final acceleration near the target to meet the 2200 m/s at the target (Figure 11). The main drawback of this configuration is an excessive time of flight. This special energy management configuration is characterized by three consecutive thrust profiles. The initial boost phase brings the missile to some relatively slow speed. After burn out of the first boost phase, the missile coasts (decelerates) towards the target. When near the target, a second boost phase accelerates the missile to the desired kinetic energy. Since most of the missile flight occurs at a relatively slow speed, energy loss due to drag is minimized. For this reason, the dual-impulse configuration is less demanding on the propulsion system. The main drawback is a longer reaction time (time of flight); because of the low speed of the missile, the engagement time is increased by a factor 3 to 10 at maximum range.

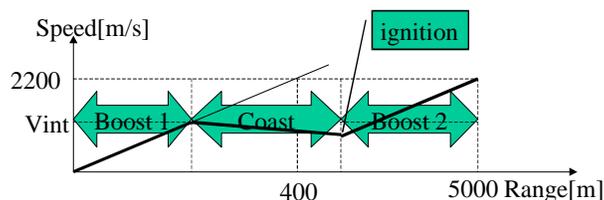


Figure 11: Boost-coast-boost configuration velocity profile

### 3.3.4 Two-stage coasting dart configuration:

This configuration is a two-stage missile, specifically a booster-dart arrangement. After the boost phase, the small diameter dart containing the penetrator separates from the booster and continues its flight towards the target. The maximum speed required before separation is lower than in the unitary configurations 1 and 2, since the dart offers a lower aerodynamic drag during its flight to the target. Accordingly, a lower energy expenditure is required from the booster, hence a smaller booster propellant mass.

The separation of the dart represents a significant technical challenge. The two stages must be guided in order to achieve the short and long range specifications, hence two different sets of control actuators. Different volume envelopes mean that the control systems will likely be different for the two stages.

### 3.3.5 Two-stage sustained dart configuration:

The two-stage sustained dart configuration is similar to the previous one except that the dart assembly is equipped with a sustain motor to maintain a constant speed up to the target. Since the small diameter dart offers a small drag, the thrust needed remains small. An analysis of the performance obtained with this configuration shows that the added complexity of installing a motor on the dart is not worth the performance gain.

## 3.4 Preliminary concept results

Figure 12 presents the mass distribution of the five competing concepts.

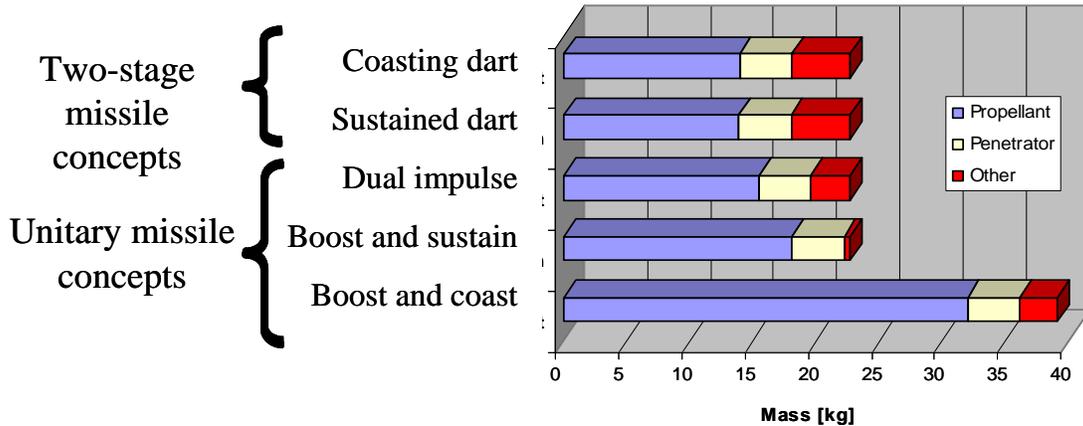


Figure 12: Mass distribution of concepts for a 23 kg missile

Only two of three unitary configurations do not allow us to agree with the specifications within a reasonable propellant mass. These two configurations were rejected.

Two-stage configurations are the configurations which require the smallest fuel mass. The sustained dart has a small weight advantage over the coasting dart. This advantage is however small. The benefits of a sustain-motor are marginal. The principal disadvantage of these configurations is the complexity of separation and the problem of the guidance of each phase. The same system of guidance can be used with difficulty for both the pre- and post-separation.

The unitary dual-impulse configuration requires more fuel than two-stage configurations but remains interesting. The principal advantage is at the level of the controls. The projectile preserves the same dimension and can use the same guidance in all phases. The principal disadvantage is the increase in the time of flight. Whereas two-stage configurations require 2.5 s to reach 5000 m by maintaining 2200 m/s, depending on the parameters, the dual-impulse configuration takes between 6.5 and 25 s and minimal speed right before the second *boost* vary 100 m/s with 700m/s. Since a time of flight of 25 s and a speed of 100 m/s is unacceptable, there are thus constraints on the aerodynamics and the initial mass of the projectile. The time of flight and minimal speed are therefore sensitive to the mass of the vehicle and aerodynamics. The minimization of the time of flight passes by the improvement of aerodynamics and/or a heavier projectile having the same drag.

At this point, it was suggested to continue the investigation of the two-stage configurations with a coasting dart. This decision was a decisive milestone for the project.

### 3.5 Sensitivity of the two-stage configuration with coasting dart to design parameters

A subset of the results generated during this study is presented for brevity, namely, the performance of two-stage configuration with coasting dart. First, the performance of the configuration with nominal design parameter values is presented. Table 2 shows the user-specified parameters that served as inputs to the motor sizing loop. Table 3 indicates the parameters obtained from the optimization and key performance figures. Figure 13 plots trajectory parameters of interest.

*Table 2. Nominal parameters*

<b>Parameter</b>	<b>Value</b>
Aerodynamic coefficient scaling [%]	100
Booster diameter [m]	0.145
Dart diameter [m]	0.04
Propellant specific impulse [s]	260
Total missile mass [kg]	22.679
Initial missile velocity [m/s]	4
Mass of the coasting dart [kg]	7

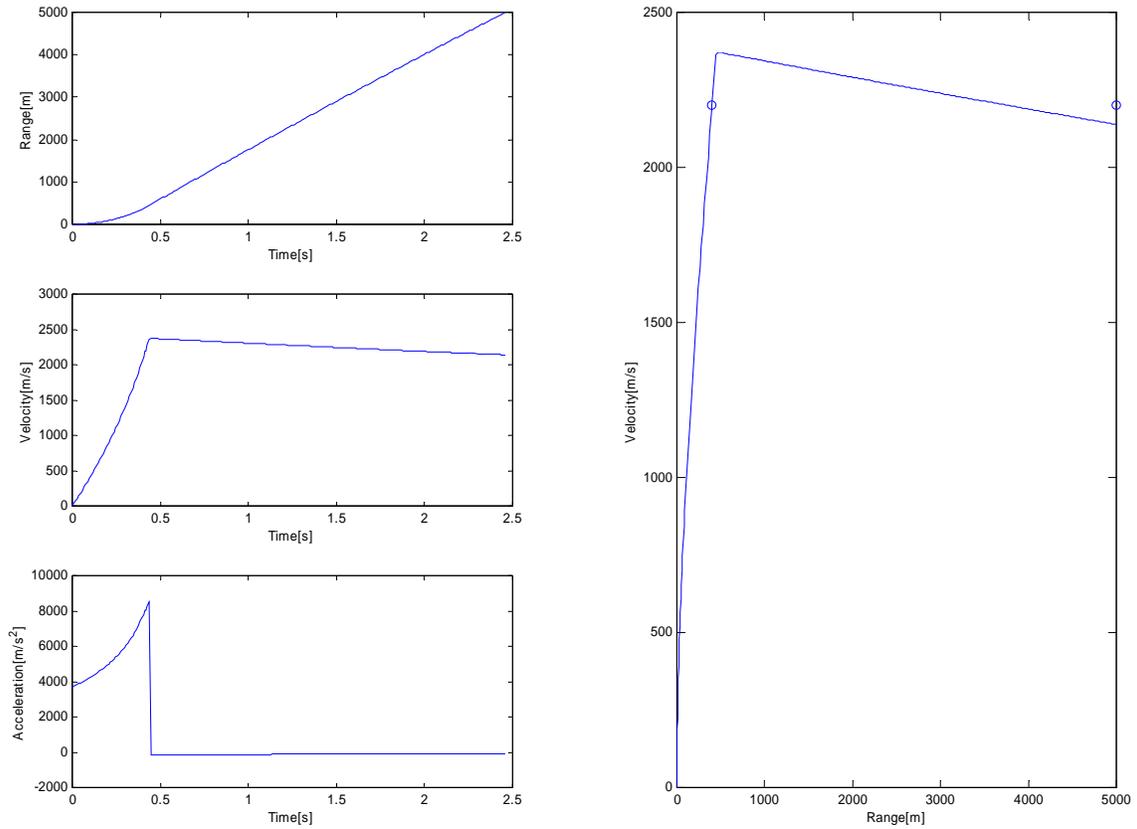


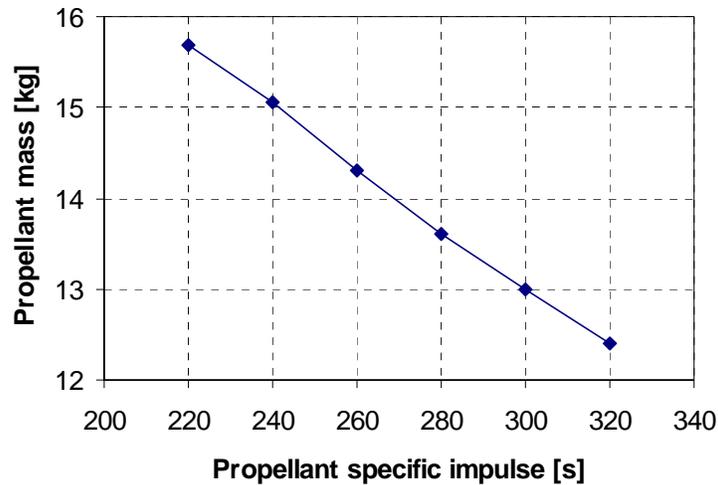
Figure 13: Nominal configuration trajectory

Table 3. Nominal performance

Parameter	Value
Propellant mass rate [kg/s]	32.67
Propellant mass [kg]	14.30
Propellant mass fraction [%]	63
Propellant burn duration [s]	0.438
Maximum velocity [m/s]	2372
Maximum acceleration [m/s <sup>2</sup> ]	8489
Time-of-flight to 5000m [s]	2.458

Second, the results of a sensitivity analysis of the propulsion and aerodynamics parameters are presented. In this sensitivity analysis, the amount of propellant mass required to achieve the mass-speed-range specification is shown.

Figure 14 shows that the missile is sensitive to the propellant specific impulse, as this parameter directly impacts the amount of propellant required.



*Figure 14: Propellant mass sensitivity to propellant specific impulse*

The next figures show that the missile performance is not very sensitive to variations of the aerodynamic drag from different body diameters (Figure 15) and drag coefficients (Figure 16). The mass of propellant required varies only slightly in these cases, because most of the energy expenditure is for the acceleration phase of the booster-dart, rather than to counter the drag of the small diameter penetrator during its separated flight.

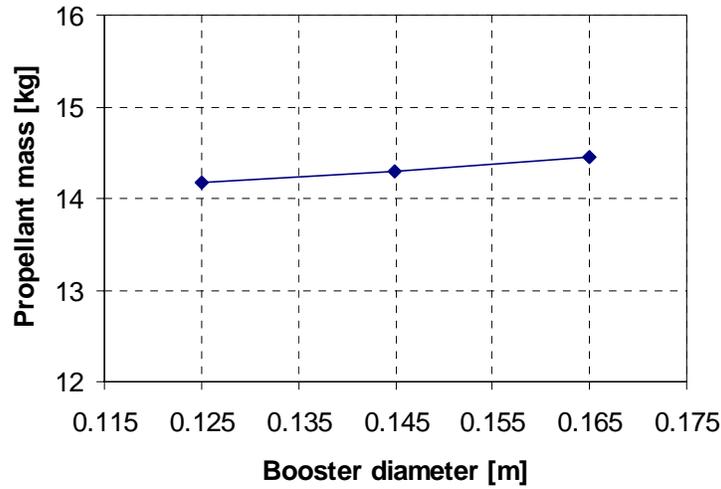


Figure 15: Propellant mass sensitivity to booster diameter

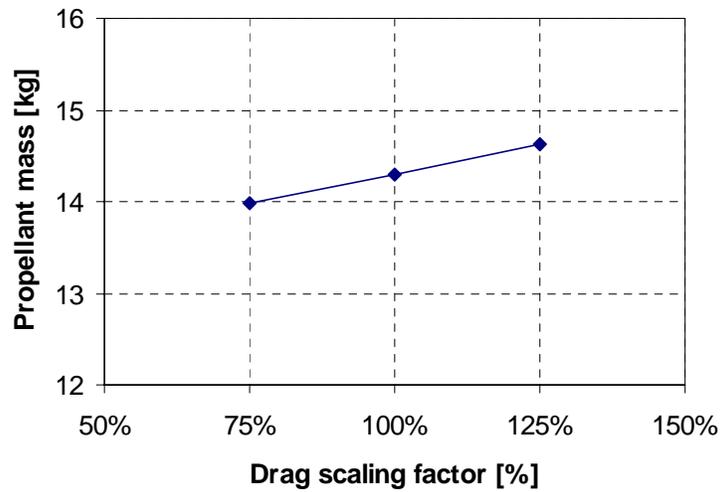


Figure 16: Propellant mass sensitivity to drag

Because of the weak total influence of the aerodynamic drag of the separated projectile, these configurations are not very sensitive to the aerodynamics and the diameter of the booster rocket. For the same reason, the initial mass of the projectile affects the performances only slightly. The total mass will thus have to be dictated by the on-board mass of the components of guidance and control and the specific impulse of the propellant used in the motor.

### **3.6 Retained configuration**

The HEMi missile flight of the two-stage configuration with a coasting dart consist of three phases, the boost phase, the separation phase and the guided dart flight.

The boost phase lasts for the first 0.4 sec and 400 m of flight. During this period, the rocket motor accelerates the missile to Mach 7 while the guidance, based on thrust vector control, brings the missile on the launcher-to-target line-of-sight.

At 400m, the missile has reached its velocity and is on line-of-sight. A target engagement at this range would have the greatest chance of success. However, if a target is at shorter range, the missile may miss the target because launch transients are not yet totally cancelled by the guidance. In addition, even if the missile hits the target, the lower missile velocity may provide insufficient kinetic energy to penetrate the target armour.

When the missile reaches 400 m, the missile is stabilized on the line-of-sight and the motor burning ends. The unguided separation phase begins. The dart slides out of the booster over a range of about 100-200 m. No guidance is possible during this phase because any lateral control force would hurt the separation. For this reason, during this phase, the missile accuracy slightly decreases. It is also during this period that the dart extends. This process increases the penetrator lethality.

During the dart guidance phase, the missile guides to the target. The dart drag causes the missile to decelerate progressively.

Following the preliminary concept definition leading to the choice of a two-stage configuration with coasting dart, the concept has been further defined and simulated.

## 4. Parametric studies of the concept

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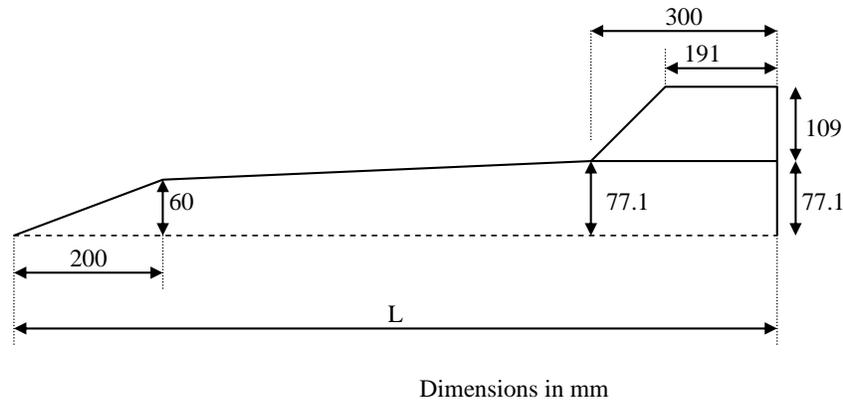
In order to refine the concept, a series of parametric studies has been performed to evaluate the most appropriate booster shape to achieve the kinematics objective within the allowed mass and length constraints.

The first study varied the booster length in order to achieve the required velocity, the second study varied the diameter, while the third evaluated the use of a flared booster to provide aerodynamic stability instead of using fins.

For each variation of the HEMi missile, the technology leaders for the structure, propulsion and aerodynamics provided a set of parameters to customize the simulation to the individual concept considered in the parameter study.

### 4.1 Study A: Booster length parametric variation

This study varied the booster length in order to achieve the required velocity. The booster shape is illustrated in Figure 17.



*Figure 17: Booster shape for length parametric study*

The parameters used are presented in Table 4 and results for the velocity in Figure 18. Figure 19 presents the resulting missile mass.

Table 4: Parameters for the booster length parametric study

Case	Total length L (mm)	Propellant mass (kg)	Missile mass (kg)	Velocity at 400m (m/s)	Velocity at 5km (m/s)
Baseline	1250	14.64	23.00	2342	2090
Study A 1250	1250	14.64	24.36	2101	1858
Study A 1325	1325	15.88	25.86	2175	1930
Study A 1400	1400	17.12	27.36	2243	1994
Study A 1475	1475	18.37	28.86	2306	2054
Study A 1550	1550	19.61	30.37	2364	2110
Study A 1625	1625	20.85	31.87	2419	2162

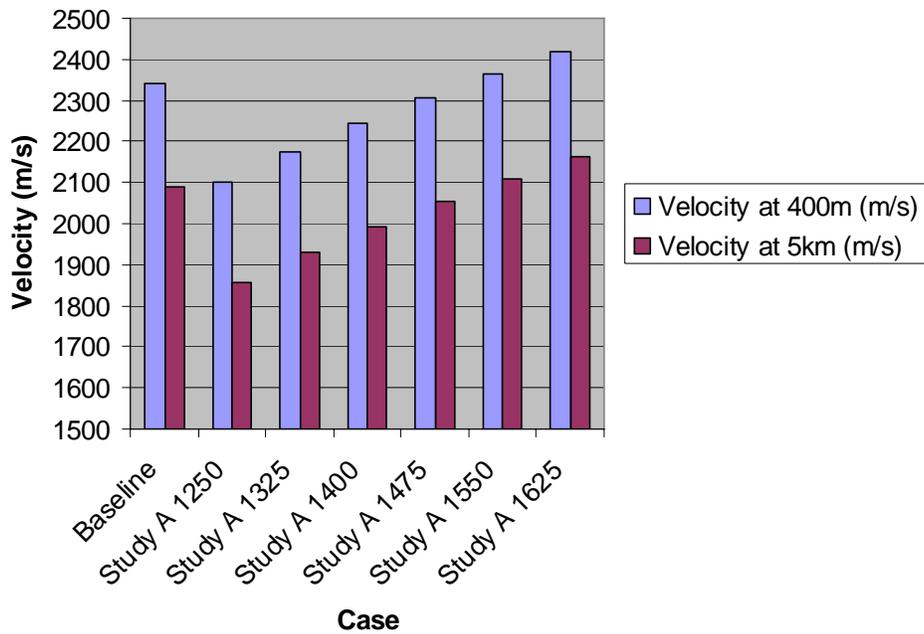


Figure 18: Missile velocity for the booster length parametric study

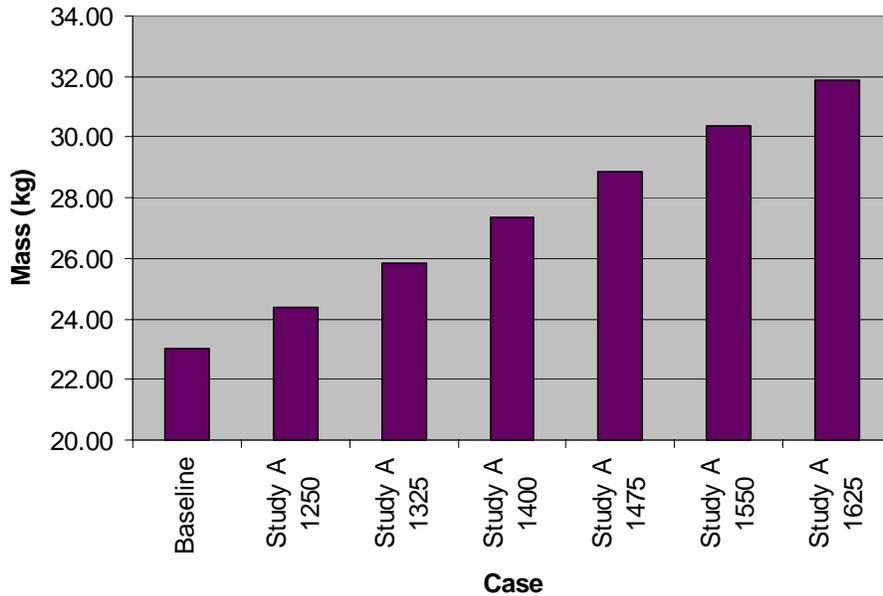


Figure 19: Missile mass for the booster length parametric study

The results show that increasing the length of the booster allows us to obtain the required velocity of 2200m/s but that the total system weight systematically exceeds the 23 kg requirement.

## 4.2 Study B: Booster diameter parametric variation

To evaluate if a longer missile with a smaller diameter would improve on the previous configuration, this study varies the booster diameter in order to achieve the required velocity. The booster shape is illustrated in Figure 20.

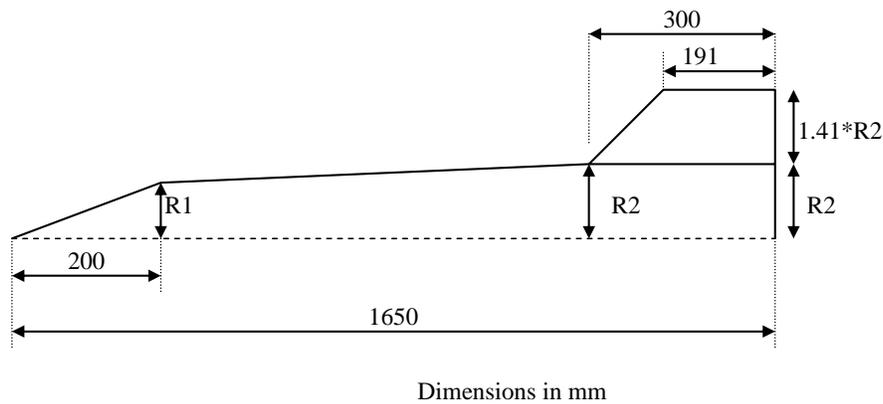


Figure 20: Booster shape for the length parametric study

Parameters used are presented in Table 5 and results for velocity in Figure 21. Figure 22 presents the resulting missile mass.

Table 5: Parameters for the booster diameter parametric study

Case	Nozzle radius R2 (mm)	Nose radius R1 (mm)	Propellant mass (kg)	Missile mass (kg)	Velocity at 400m (m/s)	Velocity at 5km (m/s)
Study B 77.1	77.1	60.0	21.27	32.37	2436	2177
Study B 76.1	76.1	59.0	20.70	31.75	2408	2153
Study B 75.1	75.1	58.0	20.14	31.13	2379	2123
Study B 74.1	74.1	57.0	19.58	30.52	2350	2097
Study B 73.1	73.1	56.0	19.04	29.93	2321	2071

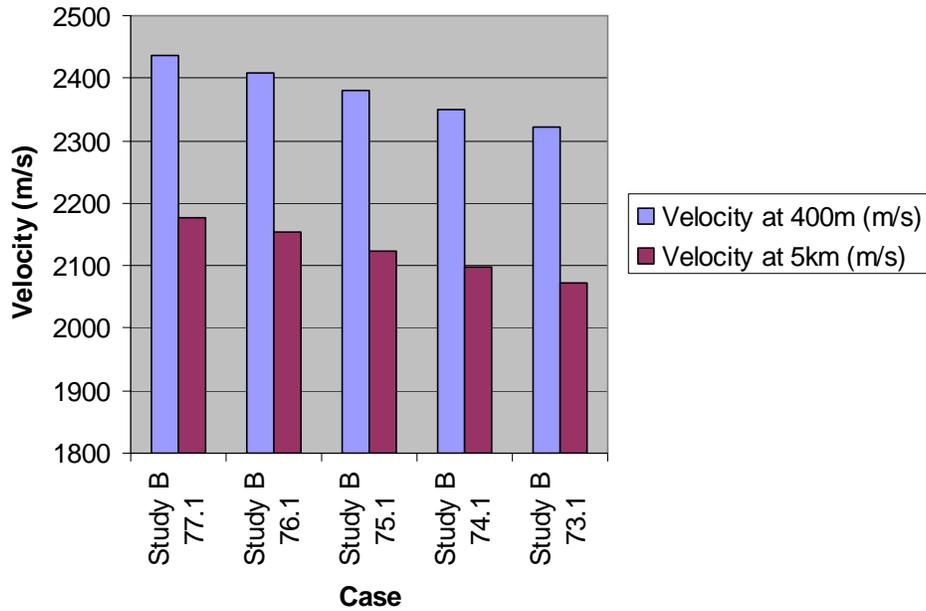


Figure 21: Missile velocity for the booster diameter parametric study

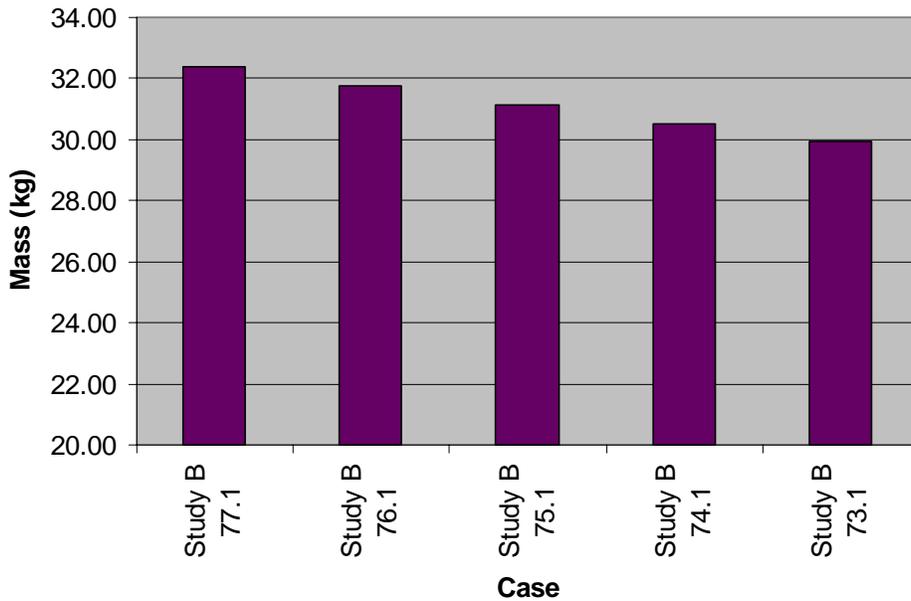


Figure 22: Missile mass for the booster diameter parametric study

The results show that again, it is impossible to achieve a total system weight of 23 kg as per requirement, at the required velocity of 2200 m/s.

### 4.3 Study C: Booster flare parametric study

An alternate configuration is to use a flared booster tail to provide aerodynamic stability instead of using fins. The booster shape is illustrated in Figure 23.

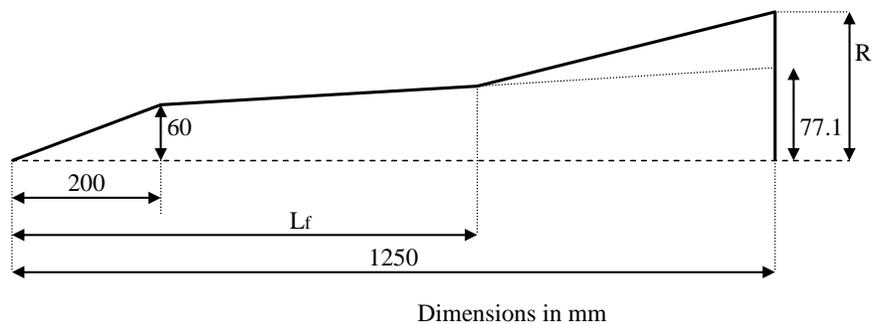


Figure 23: Booster shape for the flare parametric study

Parameters used are presented in Table 6 and results for velocity in Figure 24. The system mass is constant.

*Table 6: Parameters for the booster flare parametric study*

<b>Case</b>	<b>Nozzle radius R (mm)</b>	<b>Flare base position Lf (mm)</b>	<b>Propellant mass (kg)</b>	<b>Missile mass (kg)</b>	<b>Velocity at 400m (m/s)</b>	<b>Velocity at 5km (m/s)</b>
Baseline no fins	77.1	-	14.64	24.36	2143	1898
Study C A200	100.0	200	14.64	24.36	2203	1954
Study C A410	100.0	410	14.64	24.36	2202	1953
Study C A620	100.0	620	14.64	24.36	2200	1952
Study C A830	100.0	830	14.64	24.36	2198	1950
Study C A1040	100.0	1040	14.64	24.36	2186	1940
Study C B200	87.5	200	14.64	24.36	2176	1931
Study C B410	87.5	410	14.64	24.36	2176	1931
Study C B620	87.5	620	14.64	24.36	2176	1931
Study C B830	87.5	830	14.64	24.36	2175	1930
Study C B1040	87.5	1040	14.64	24.36	2174	1929

Results shows that a larger nozzle radius (i.e. diameter of the flare) is beneficial. Although this increases aerodynamic drag, the increased thrust generated by the larger nozzle exceeds the drag force thus leading to improved performance.

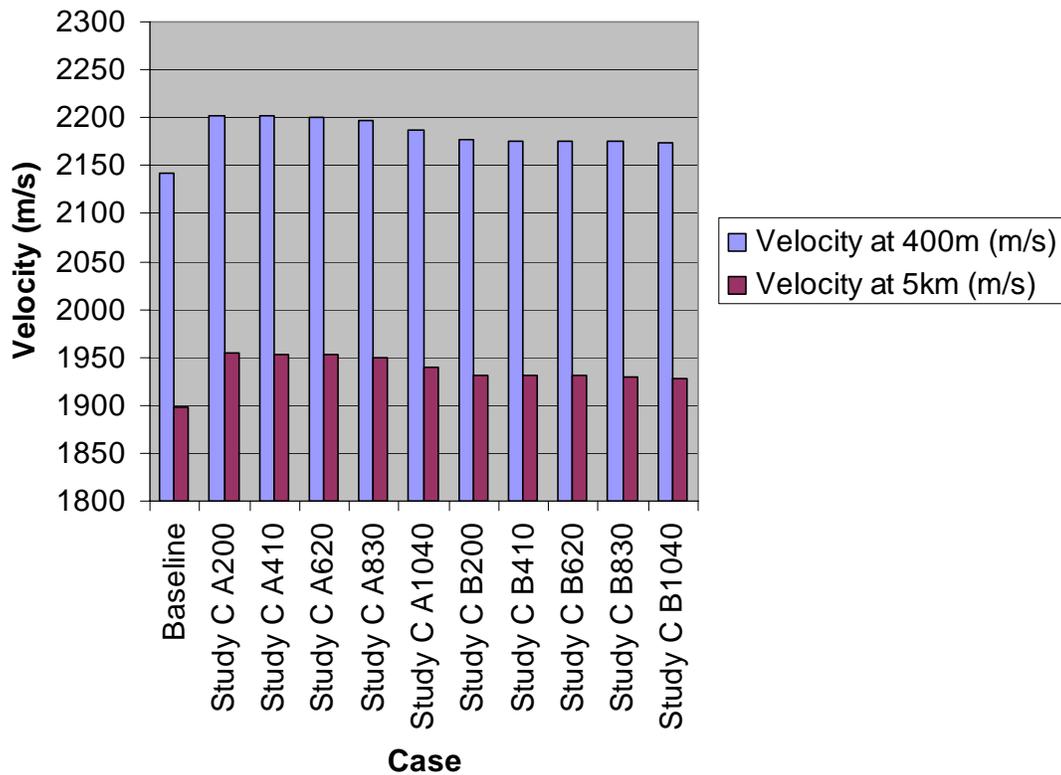


Figure 24: Missile velocity for the booster flare parametric study

#### 4.4 Limitations of parametric studies based on parameter sets

Based on the results of the parametric studies of the previous section, several limitations to the simulation methodology have been observed. First, for a missile like HEMi, the number of design variables is so large that the number of possible designs is endless. The previous parametric studies failed to find a design that can successfully meet the required system specifications.

In addition, the preparation of multiple parameter sets for parametric studies is time consuming. The library of model components and parameter sets is derived from DRDC experience gained on modelling existing systems. For existing systems, the analysis of technologies (e.g. use of aerodynamic prediction code to estimate aerodynamic coefficient, analysis of solid rocket motor booster to estimate time-thrust curve, mass measurement) can be performed independently and once for all. However, for the refinement of the HEMi concept, the team organization required repeated modelling and analysis of each evolution of the concept.

Figure 25 presents the flow chart of activities for the HEMi refinement process. The HEMi team conducted an analysis of the system performance results and discussed deficiencies and solutions together at a working meeting in order to propose modification and trade-studies to potentially

improve the performance of the concept. The concepts were captured in a drawing or a description. For HEMi, this information was captured in different formats: CAD drawing, sketches, plots, spreadsheets, e-mail, word processing file, etc. The multiplicity of formats has made it difficult to perform configuration management and tracking of the origin, reason for and/or version of the information provided.

Based on the description at any one time, technology team members performed an analysis of that technology in order to provide information to the modelling and simulation team leader, including aerodynamic coefficients, system mass, thrust profile, guidance and control algorithms, and system lethality.

This information is entered in parameter sets for simulation of the performance of HEMi.

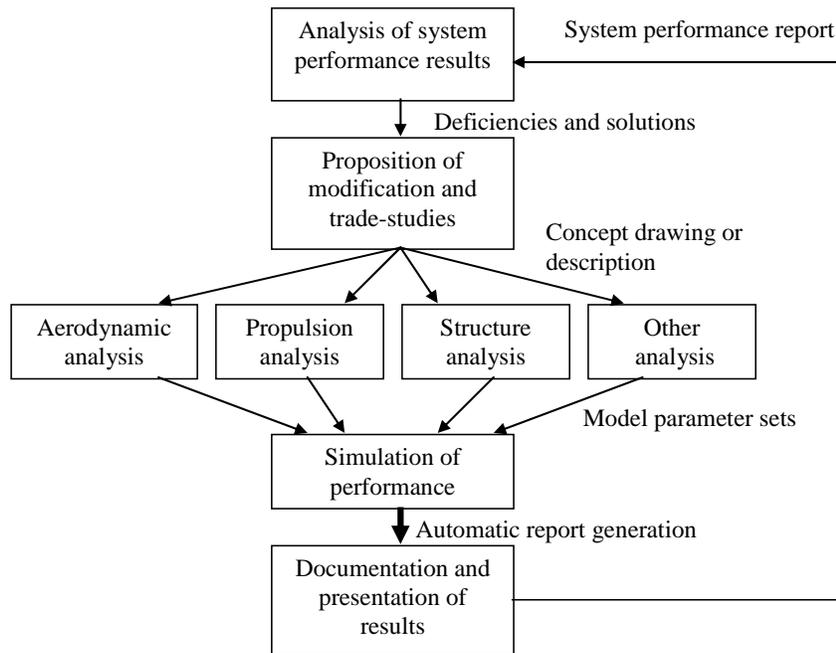


Figure 25: HEMi concept refinement process

Except for the automated report generation procedure that provides a formal method to perform a documentation and presentation of results obtained by simulation, the HEMi concept refinement process was largely informal. As a result, the iteration cycles were becoming longer when the number of variables and the level of detail of the concept development would increase. Furthermore, this was not helping the team to achieve the stringent performance specification of HEMi.

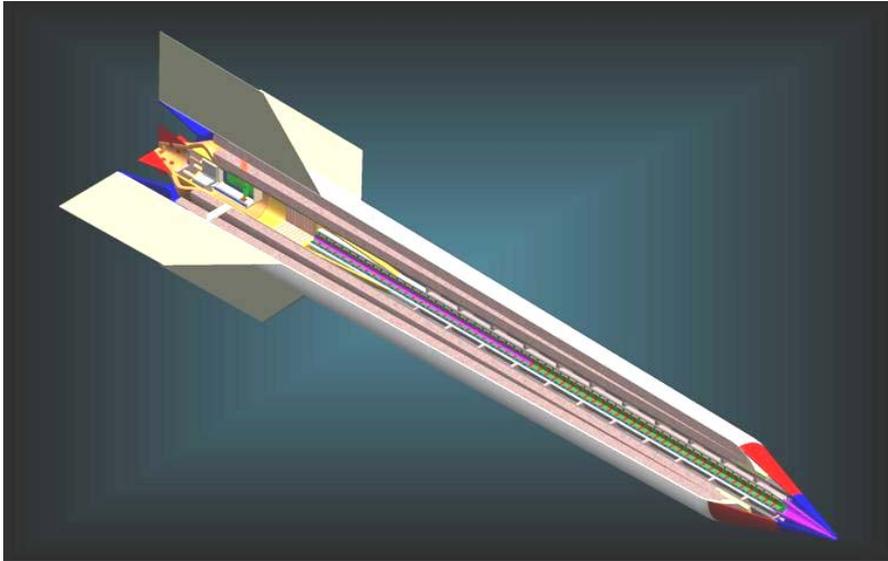
Because parametric studies were not providing outstanding performance improvements and that refinement iteration cycles were time consuming, the baseline configuration [7] was retained for further detailed design.

The detailed design allows the technologies to evolve, the missile concept to include the dart separation mechanism, detailed nozzle shape, refine the structural definition and advance the construction of the guidance and control module. The next section presents the performance of the latest detailed concept of HEMi, namely, Version 2.02.

## 5. Performance of the HEMi concept V.2.02

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Compared to the model used for parametric studies that intended to evaluate the missile kinematics than its accuracy, the latest model of the HEMi concept [8] includes more accurate representations of the guidance and control laws [9], actuators responses [10] and environmental disturbances such as launch tip-off, motor thrust misalignment, cross wind and booster-dart separation effects.



*Figure 26. HEMi V.2.02*

A nominal simulation [11] using constant disturbances composed of boost motor thrust misalignment and dart separation effects allowed for the evaluation of the nominal kinematics performance of the missile. Then, a Monte Carlo simulation [11] using randomly generated disturbances was used to evaluate the dispersion and probability of hit of the missile.

### 5.1 Simulation of nominal engagement

In order to evaluate the kinematic performance of the HEMi missile against its performance specifications [6, 7], a nominal simulation scenario of the missile using deterministic disturbances is performed.

The simulation parameters include the initial conditions of the booster at the exit of the launch tube, the environment parameters, motor thrust misalignment and the effects of the separation of the dart from the booster. In this scenario, deterministic values are used.

The two types of disturbances used here are a thrust misalignment on the booster motor and a dart separation tip-off. Figure 27 presents the trajectories for target ranges of 400 m and 5000 m.

These two target ranges have been selected because they represent the minimum and maximum range requirements. Since all simulated disturbances are in the vertical plane, only results for this plane are presented since no manoeuvres occur in the horizontal plane.

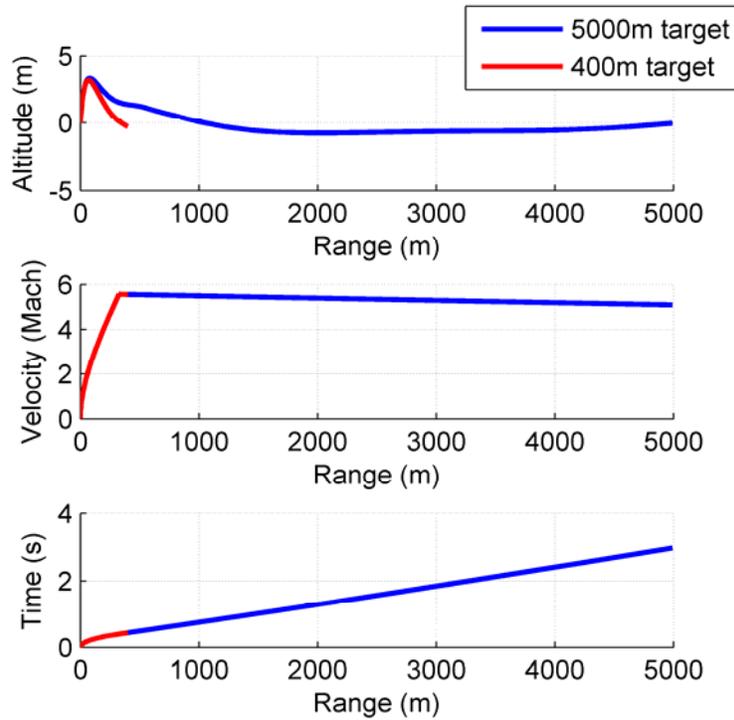


Figure 27. Nominal engagement results

Figure 28 presents the angular information for the same simulations. Results show that the maximum velocity is obtained at a range of 325 m. The design objective was to attain a 400 m range in 0.4 s at Mach 6.5. However, because of its excess weight, the missile reaches a maximum velocity of only Mach 5.6 at 325 m in 0.4 s.

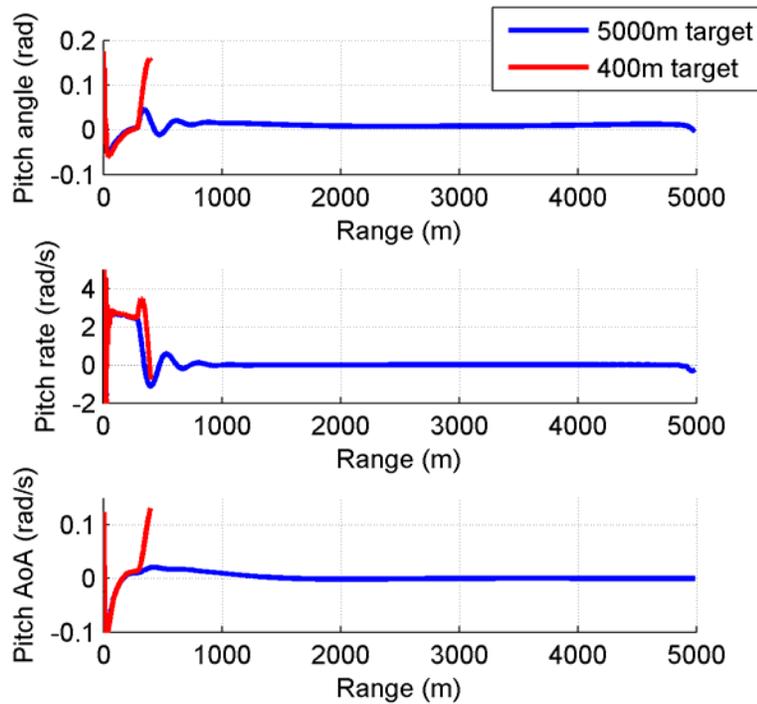


Figure 28. Nominal engagement results(2)

At the end of boost at 325 m, the booster is stabilized at a small angle of attack.

For a long range target at 5000 m, the dart coasts with minimum corrections. At 5000 m, the dart has decelerated to Mach 5.6.

## 5.2 Monte-Carlo simulation

In order to compute the dispersion and accuracy performance of HEMi, this section presents the parameters and results of a Monte-Carlo simulation. Here, the simulation is run repetitively with specific parameters selected randomly according to their estimated distribution.

The simulation has been performed for target range varying from 100 m to 5000 m. For each range, 100 missile simulations have been performed with the parameter distributions defined in Table 7.

**Table 7. Monte-Carlo random parameters[11]**

Wind vector [North, East, Down] (m/s)	$\begin{bmatrix} N(0,25) \\ N(0,25) \\ N(0,25) \end{bmatrix}$
Yaw thrust misalignment angle (rad)	$N(0,0.000025)$
Pitch thrust misalignment angle (rad)	$N(0,0.000025)$
Separation induced pitch rate (rad/s)	$N(0,1)$
Separation induced yaw rate (rad/s)	$N(0,1)$

Compilation of the simulation results is presented in Figure 29. The first plot presents the 50% and 95% circular error probable (CEP) dispersions. These represent the radius of circular targets that contain respectively 50% and 95% of all missile impacts.

The second plot of Figure 29 presents the probability of hit for a square target of 1 m x 1 m and for a standard NATO target of 2.3 m x 2.3 m.

Results show that at any range, the missile meets the 95% probability of hit requirements for a standard 2.3 m x 2.3 m NATO target.

For ranges less than 800 m, disturbances created by motor thrust misalignments and dart separation disturbances slightly decrease the missile accuracy. For long range targets, the dart guidance fully compensates for the disturbances and achieves greater accuracy on target. However, the missile model does not account for guidance sensor induced errors. It is expected that modelling the guidance sensor accuracy will increase the missile dispersion at the longer ranges.

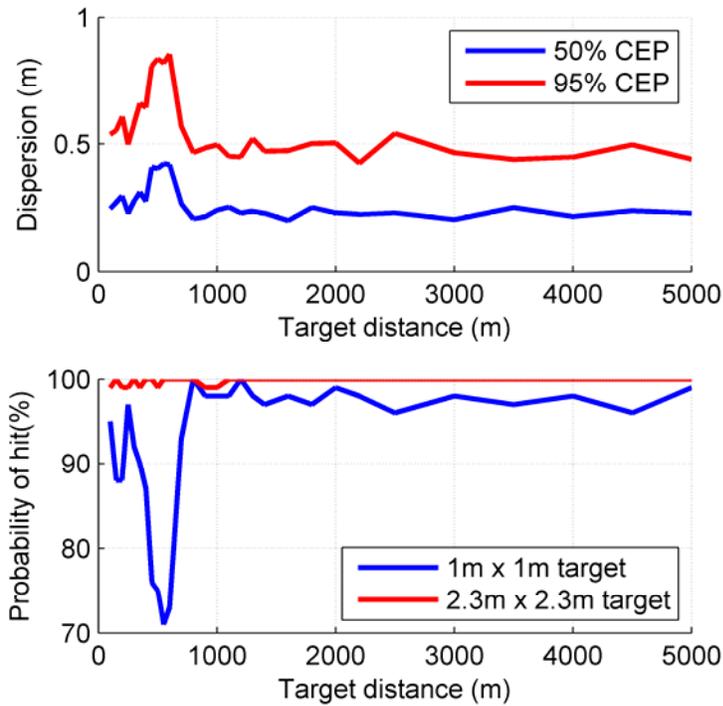


Figure 29. Dispersion and probability of hit as a function of target range.

### 5.3 Summary of performance

In support of the development of the HEMi concept, analysis of the missile performance has been performed using modelling and simulation of the engagement.

A nominal simulation using constant disturbances composed of boost motor thrust misalignments and dart separation effects permitted the evaluation of the nominal kinematics performance of the missile.

Then, Monte Carlo simulations using randomly generated disturbances were used to evaluate the dispersion and probability of hit of the missile.

Table 8 presents a summary of the achieved HEMi missile performance by comparison with the design objective from the missile system level specifications [7].

**Table 8.** Summary of HEMi performances

<b>Characteristic</b>	<b>Objective</b>	<b>Achieved</b>
Mass (kg)	23	25.8
Length (m)	1.25	1.264
Minimum range(m)	400	325
Maximum range(m)	5000	5000+
Top speed (Mach)	6.5	5.6
Flight time to 5000m (sec)	2.4	3.0
Hit probability (400-5000m, 2.3x2.3m stationary target)	95%	95+%

The rocket motor having been designed for a missile mass of 23 kg, the actual overweight mass of 25.8 kg leads to a maximum velocity of Mach 5.6 while the objective was Mach 6.5.

Top speed is obtained at a range of 325 m, thus achieving a minimum engagement range shorter than the 400 m objective.

The Monte Carlo simulation results demonstrate that a hit probability of at least 95% can be achieved for all target ranges. However, the missile model does not account for error induced by the guidance sensor. It should be expected that modelling the guidance sensor inaccuracies would increase the missile dispersion at long range. Also, further work is required to estimate the probability of kill of the proposed segmented rod.

## 6. Integrated analysis and multidisciplinary optimization

In order to increase the pace of the HEMi concept refinement process, an effort was made to integrate into a single architecture many of the engineering analysis codes used for the analysis and definition of the model parameter sets of HEMi. The aerodynamic estimation is made using the Missile DATCOM software [12]. Nozzle length is computed as a function of the nozzle exit radius, nozzle cone angle and throat area. The propellant performance module computes the thrust, specific impulse and mass flow rate of the propellant as a function of the chamber pressure and nozzle throat and exit areas. Case and retention tube thickness and weight are computed as a function of the chamber pressure and wall material properties. Using a one-degree of freedom simulation, the required mass of propellant is adjusted.

Figure 30 presents the interdependency of design and analysis codes in the integrated analysis architecture.

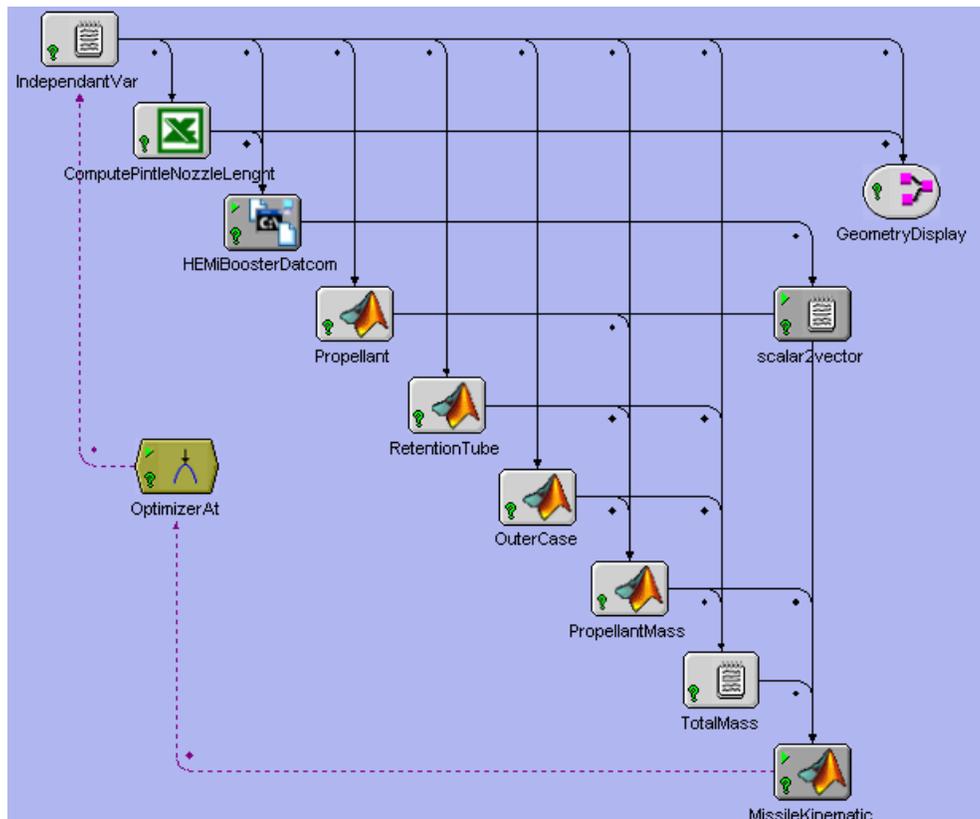


Figure 30: Interdependency of design and analysis codes in the integrated analysis architecture

The integration of the analysis codes permitted the linking of the interdependent variables, thereby allowing for a multidisciplinary analysis of the HEMi concept. The codes were integrated in the Phoenix Integration Model Center, which offers tools for parametric analysis and design of experiment.

However, the greatest benefit from this integrated analysis architecture is the possibility to use an optimization algorithm to vary the concept independent variable, in order to optimize the performance of the system and provide a true multidisciplinary optimization [13].

To differ with HEMi simulation tools initially implemented, the integrated approach does not only simulate a specific instance of a concept but also allows us to simulate a whole family of concepts defined using some independent variable that can be varied infinitely. Emphasis is on simulation of the feasible family of systems rather than a single point design high-fidelity simulation.

## 6.1 Achievement in HEMi concept optimization – focus on booster configuration

As demonstrated in parametric studies, achieving simultaneously the length, mass, and speed (lethality) requirement is challenging. There are in fact three main requirements:

Building a missile that complies with the 1.25 m length constraint is straightforward. However, respecting the maximum mass is more challenging because it requires the determination and concordance of a mass distribution budget for all components. Also, given the challenging requirements, it is likely that even if the mass distribution is optimized, the speed and thus lethality specifications may not be met.

For the optimization of the HEMi concept, the team has decided that the most important requirement to respect is the speed because it directly impacts the intended effect (lethality and response time) of the missile system.

Given that the missile length is an independent variable (i.e. it can be build any way, without saying a priori that it will work though) and that the velocity is the most independent requirement, the objective of the design optimization work for the HEMi booster was to determine the missile configuration that provides the lightest system while achieving speed performance and payload objectives.

The resulting optimization problem definition is presented in Table 9.

*Table 9: Optimization problem definition*

<p><b>Optimization objective:</b></p> <ul style="list-style-type: none"> <li>– <b>Minimize total motor mass</b> <ul style="list-style-type: none"> <li>• Propellant + case + nozzle mass</li> </ul> </li> </ul>
<p><b>Design variables:</b></p> <ul style="list-style-type: none"> <li>– Missile sizing (length and diameter) <ul style="list-style-type: none"> <li>• Effect on drag, propellant volume and weight</li> </ul> </li> <li>– Chamber pressure</li> </ul>

<ul style="list-style-type: none"> <li>• Effect on propellant specific impulse</li> <li>• Effect on motor case thickness <ul style="list-style-type: none"> <li>– Effect on weight (function of case material)</li> </ul> </li> <li>– Nozzle throat area <ul style="list-style-type: none"> <li>• Effect on the motor burn-rate</li> </ul> </li> </ul>
<p><b>Constraints:</b></p> <ul style="list-style-type: none"> <li>– Achieve a missile velocity of 2400m/s (Mach 7)</li> <li>– in a range of 400m</li> <li>– Given overall missile length</li> </ul>

Figure 31 presents the missile mass of the optimized design as a function of the overall missile length selected. For comparison, the numbers for the targeted design and the achieved current design V.2.02 are presented.

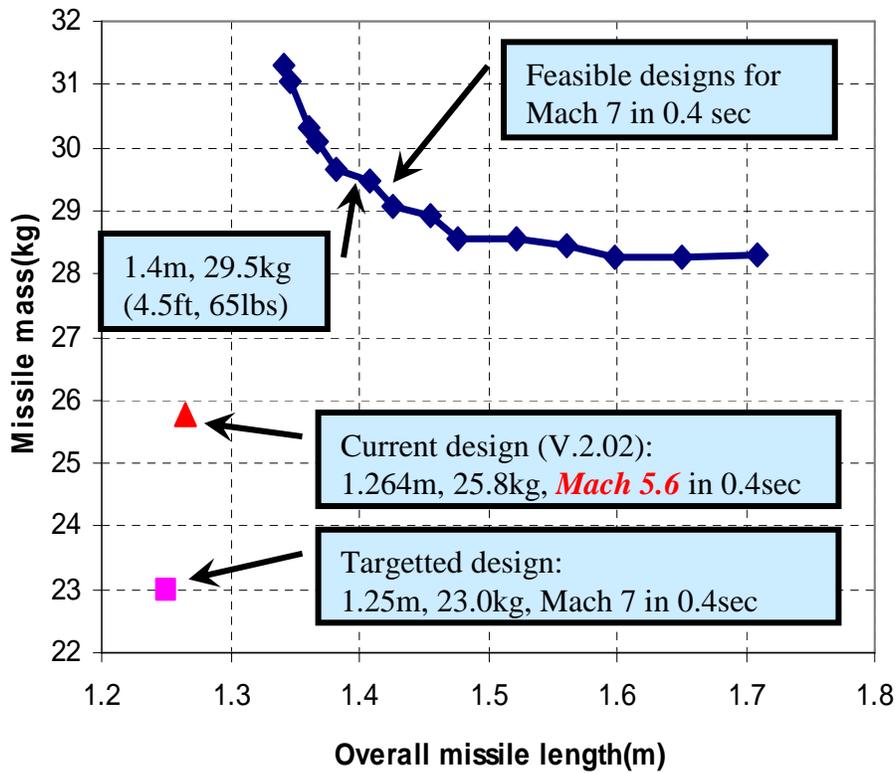


Figure 31: Design feasibility domain for HEMi

The important conclusion that can be drawn from that figure is that the integrated design codes indicate that the technology they represent cannot achieve the initial specification of a total missile length of 1.25 m, a mass of 23.0 kg and a velocity of Mach 7 in 0.4 s.

The current design reaches only Mach 5.6. However it is possible to reach Mach 7.0 by increasing both the length and the mass of the missile. Table 10 presents a tabular comparison of the results of Figure 31.

*Table 10: Comparison of designs*

<b>Design</b>	<b>Length(m)</b>	<b>Mass(kg)</b>	<b>Velocity (Mach)</b>
Targeted design  (not feasible with the state of the technology captured by the integrated design codes)	1.25	23.0	7.0
Current design (V.2.02)  (feasible but Mach 5.6 only)	1.264	25.8	5.6
A feasible example at Mach 7.0	1.40	29.5	7.0

At the difference of parametric studies that vary independent variables using discrete values, the use of optimization allows one to hold, using optimization constraints, the values of dependent values such as velocity and mass. This allows restricting the concept investigation to only concepts that meet specific requirements.

## **6.2 Limitations and benefits of design methods based on integrated analysis and optimization**

Missile system design requires high levels of integration among disciplines such as aerodynamics, structures, propulsion, and controls. These disciplines are mutually interactive and coupled and these effects must be fully considered in the analysis of missiles and in the prediction of system responses.

This is particularly true for HEMi since the length, weight and velocity requirements demand state-of-the-art technologies. Figure 32 presents a technology interaction matrix for HEMi. This matrix presents with which factors each key technology of HEMi interacts. The matrix could present several other factors but presently contains enough information to state that all technologies are interrelated.

Propulsion					
Aerodynamic					- Booster size and length - Drag
Control				- Canard design - Aero heating - Control forces and moments	- Thrust misalignment - TVC design
Lethality			- Accuracy - Angle of penetration	- Angle of penetration - Velocity	- Velocity
Guidance		- Terminal accuracy	- Bandwidth - Update rate	- Control authority	- Smoke/plume
Structure	- Packaging	- Bending stiffness	- Bending frequency - Volume	- Wing attachment - Separation	- Weight - Pressure - Integrity - TVC

Figure 32: Technology interaction matrix

Modelling and simulation is required to assess the integrated effect of the proposed technologies on the factors presented in the figure. The system performance model and the analysis fully consider the interaction between disciplines and technologies.

The use of optimization to conduct the design and analyze the system provides an automated way to tailor a conceptual weapon design to user defined requirements. The entire spectrum of capabilities provided by the weapon can be investigated using parametric variations of the weapon performance requirements. If several weapon configurations can achieve a given performance requirement, the use of optimization based design allows one to define the best configuration according to a performance criterion such as minimum take-off weight, minimum flight time or minimum cost.

However, when model complexity is augmented, the direct optimization of a missile system including disciplines such as aerodynamics, structures, propulsion, and controls becomes unpractical due to excessive computational cost and complexity. Complex model optimization methodologies based on multidisciplinary hierarchical optimization can be investigated to improve the performance of the optimization algorithm by taking advantage of the problem decomposition into subsystems. The most promising method, Bi-Level Integrated System Synthesis (BLISS), divides the optimization problem into two levels: system (weapon) and subsystems (e.g. aerodynamics, structures, propulsion, and controls). The main system optimization coordinates the subsystem optimizations to ensure that subsystems converge to the global system optimum.

The capability to perform optimization of complex models will deliver not only more accurate modelling and simulation results but will also define more accurately what is the best system that can result from the use of enabling technologies such as hypersonic weapons.

Since technologies are tightly integrated and coupled, individual technology improvements can be detrimental to the system performance if coupled subsystems are not adapted to the improved technologies. Additionally, a potential subsystem improvement may be detrimental to the weapon system performance once its impact on coupled subsystems is assessed.

An integrated analysis methodology can provide a fair comparison of the impact of technologies on the system performance by ensuring that they have been properly integrated with other subsystems. Sensitivity analyses of system performance to subsystem parameters can also be performed.

This allows for an adequate evaluation of technologies to aim development in the most promising directions.

## 7. Conclusions

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The simulation of the evolution of the HEMi concept required the development and maintenance of several computer models and parameter sets in order to analyze candidate technologies. To achieve this task efficiently, tools were developed for the management of simulation parameter sets, subsystem models, documentation and automated generation of simulation result reports.

During the development of HEMi, more than 130 parameter sets were generated for the 11 blocks of the library and nearly 100 simulation result reports were generated using the automated report generation methodology. This tool proved to be invaluable by providing fast, accurate and up-to-date feedback to the HEMi technology teams.

Achieving the desired kinematic performance (speed-range) within the specified HEMi missile envelope (mass-size) is a formidable technical challenge. A preliminary concept definition study was performed during the project definition phase. The objective of this study was to verify the feasibility of achieving the mass-speed-distance specification with five different airframe/thrust management configurations. Based on this study, it was decided to continue the investigation of the two-stage configurations with coasting dart.

To refine the concept, a series of parametric studies were done to determine the most appropriate booster shape to achieve the kinematic objective within the stated mass and length constraints. Based on the results of the parametric studies, several limitations to the simulation methodology were observed. First, for a missile like HEMi, the number of design variables is so large that the number of possible designs is endless. The previous parametric studies failed to find a design that successfully achieved the stated system specifications.

To expedite the HEMi concept refinement process, an effort was made to integrate in a single architecture many of the engineering analysis codes used to analyze and define the model parameter sets of HEMi. The integration of the analysis codes permitted the interdependent variables to be linked, thereby allowing multidisciplinary analysis of the HEMi concept. The greatest benefit of this integrated analysis architecture has been the possibility to use an optimization algorithm to vary the concept independent variables in order to optimize the performance of the system, thus providing in essence a multidisciplinary optimization.

Unlike parametric studies that vary independent variables using discrete values, optimization allows one to hold nearly constant the values of dependent variables like velocity and mass using optimization constraints. Missile system design requires high levels of integration between disciplines such as aerodynamics, structures, propulsion and controls. These disciplines are interrelated and interdependent, and all ramifications must be fully considered in the analysis of individual systems and the prediction of system responses. This was particularly true for HEMi, since the length, weight and velocity requirements all demand state-of-the-art technologies.

The performance of the missile was analyzed through engagement M&S. Nominal kinematic performance was evaluated by means of a nominal simulation using constant disturbances consisting of booster thrust misalignments and dart separation effects. Monte Carlo simulations with randomly generated disturbances were then used to evaluate missile dispersion and probability of hit.

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## List of symbols/abbreviations/acronyms/initialisms

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BLISS	Bi-Level Integrated System Synthesis
CAD	Computer Aided Design
$C_d$	Aerodynamic drag coefficient
DND	Department of National Defence
DRDC	Defence R&D Canada
HEMi	High Energy Missile
M&S	Modelling and Simulation
$N[a, b]$	Random number from a normal distribution of mean 'a' and variance 'b'
NATO	North Atlantic Treaty Organisation
R&D	Research & Development
TVC	Thrust Vector Control

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The capabilities of the HEMi compact hypervelocity kinetic energy missile technologies have been integrated using modelling and simulation to provide overall missile system performance including kill probability, velocity at the target, flight velocity profile, accuracy, size, mass, launch environment, etc. To achieve this task efficiently, tools for management of simulation parameter sets, subsystems models, documentation, and automatic report generations of simulation results have been developed. A preliminary concept definition study was performed during the project definition phase. The objective of this study was to verify the feasibility of achieving the mass-speed-distance specification for five different airframe/thrust management configurations. Then, a series of parametric studies were performed to evaluate the most appropriate booster shape to achieve the kinematics objective within the allowed mass and length constraints. In order to increase the pace of the HEMi concept refinement process, an effort was made to integrate in a single architecture many of the engineering analysis codes used for the analysis and definition of the model parameter sets of HEMi. The integration of the analysis codes permitted the linking of the interdependent variables, thereby allowing for a multidisciplinary analysis and optimization of the HEMi concept. An analysis of the performance of the latest version of HEMi has been performed using this modelling and simulation of the engagement.

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