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Hole growth equation related to Al-1100 witness plates

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Abstract

This memorandum presents a mathematical model to assess fragment hole area based on projectile impacting a target as a function of its velocity. Fragment Simulating Projectiles (FSP) of different mass and velocity were used for experimental trials with witness packs (WP). The analyses were performed with the latest versions of DeCaM (Debris Characterization and Modelling software) and WPAS (Witness Pack Analysis System). The hole growth equation developed is linear and includes fragment mass and velocity as parameters. This memorandum also presents other existing models and verifies their validity with experimental data. Finally, Velocity Threshold Curves (VTC) related to Al-1100 WP are presented as well in order to estimate fragment velocity from fragment mass, which is calculated using the fragment hole diameter recorded in the WP.

Résumé

Ce mémorandum présente un modèle mathématique qui permet de calculer l'aire d'un trou créé par l'impact d'un projectile sur une cible en fonction de sa vitesse. Des fragments simulant des projectiles (FSP) de masses et de vitesses différentes sont utilisés pour les essais avec des panneaux témoins. Les analyses ont été effectuées en utilisant la dernière version des logiciels 'Debris Characterization and Modelling software' (DeCaM) et 'Witness Pack Analysis System' (WPAS). Une équation de la croissance des trous contenant la masse et la vitesse du fragment est obtenue. Ce mémorandum présente aussi d'autres modèles existants et vérifie leur validité par rapport aux données expérimentales. Finalement, les courbes de vitesses limites (VTC), pour les panneaux témoins d'aluminium-1100, sont également présentées pour permettre d'évaluer la vitesse d'un fragment à partir de la masse du fragment qui est calculée en utilisant le diamètre du trou créé par celui-ci dans le panneau témoin.

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Executive summary

Behind-Armour (BA) debris generated after ballistic penetration events are recognized as being of major importance in vulnerability/lethality assessment. There are some constraints affecting characterization and modelling of these BA debris. One of those constraints is resolved in this memorandum by developing a mathematical model that will increase the accuracy of the fragment mass and velocity estimates of fragment impacting aluminium-1100 witness plates. The objective of the model is to define the hole growth ratio of the perforated hole area (A_h) on the first witness plate versus the fragment projected area (A_f).

Experimental trials were conducted with Fragment Simulating Projectiles (FSP) of different sizes. The mathematical model developed is then based on those experimental data. The analyses were performed with the latest versions of DeCaM (Debris Characterization and Modelling software) and WPAS (Witness Pack Analysis System). These analysis systems were developed at DRDC Valcartier. Experimental results show a linear relationship between hole growth ratio and velocity. Therefore, a linear model was developed to compute this A_h/A_f ratio. Other existing models were applied to experimental data to verify their validity. In this particular case, Yatteau's model developed for high velocity penetration revealed to be the most accurate with the experimental data and was combined to the developed model to perform extrapolation. The hole growth equation and the Velocity Threshold Curves (VTC) presented in this memorandum will allow further characterization of BA effects.

Y. Baillargeon and C. Lalanne. (2003). Hole growth equation related to Al-1100 witness plates. DRDC TM 2003-122. Defence R&D Canada - Valcartier.

Sommaire

Les débris derrière le blindage générés à la suite d'une pénétration balistique sont d'une importance majeure dans les études de vulnérabilité/létalité. Il existe certaines contraintes affectant la caractérisation et la modélisation de ces débris. Une de ces contraintes est résolue dans ce mémorandum qui présente le développement d'un modèle mathématique pour accroître la précision sur les valeurs estimées de la masse et la vitesse du fragment pour des plaques témoins d'aluminium-1100. L'objectif de ce modèle est de définir le rapport de l'aire perforée du trou (Ah) sur la première plaque témoin et de l'aire projetée du fragment (Af).

Les essais ont été effectués avec des fragments simulant des projectiles 'FSP' de grandeurs différentes. Le modèle mathématique mise au point est donc basé sur ces données expérimentales. Les analyses ont été réalisées avec la dernière version des logiciels de DeCaM ('Debris Characterization and Modelling software') and WPAS ('Witness Pack Analysis System'). Ces systèmes d'analyse ont été créés à RDDC Valcartier. Les résultats expérimentaux montre une relation linéaire entre la croissance des trous et la vitesse. Un modèle linéaire a donc été développé pour calculer le ratio Ah/Af. D'autres modèles existants ont été appliqués aux données expérimentales pour en vérifier la validité. Dans ce cas particulier, le modèle de Yatteau qui s'applique à des vitesses de pénétration élevées s'est révélé le plus précis et a été combiné à notre modèle pour permettre une extrapolation. L'équation de la croissance des trous avec les 'Velocity Threshold Curves' ('VTC') présentées dans ce mémorandum permettront une meilleure caractérisation des effets derrière le blindage.

Y. Baillargeon and C. Lalanne. (2003). Hole growth equation related to Al-1100 witness plates. DRDC TM 2003-122. Defence R&D Canada, Valcartier.

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1. Introduction

The objective of this document is to define a mathematical model based upon hole growth on a target witness plate using experimental data. This model will be later used to compute fragment mass and velocity. The Debris Characterization and Modelling software (DeCaM) [1,2] is combined with the Witness Pack Analysis system (WPAS) [1,2] to perform the analysis. However, many issues have to be resolved in order to get a suitable Characterization and Modeling of BA debris. This memorandum describes and demonstrates one of these issues which is the uncertainties associated with the computed fragment mass and velocity.

Another objective of this memorandum is to derive a mathematical model in order to estimate fragment mass and velocity with increased accuracy. The model will be derived from experimental data for many projectiles impacting a target. The projectiles are Fragment Simulating Projectiles (FSP) according to STANAG 4569 [3].

The model parameters are velocity and hole area on the first witness plate. The fragment area being known during experimental tests, allows the use of the ratio of the witness plate hole area divided by the fragment area. The equation found will make it possible to compute this ratio for different fragment mass and velocities.

Many models already exist to predict hole growth ratio. Those have been developed for different target materials and different fragment masses. A majority of them have been developed for high velocities while this study deals with low velocities from about 100 to 1000 m/s. However, it is interesting to see the accuracy at low velocity (extrapolation) when comparing those models with our experimental data. In this study, FSP are impacting 1mm thick Al-1100 witness plates.

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2. Hole Growth

Witness plates are placed behind a target to record fragment impacts. The hole area created by the impact is used to evaluate the fragment mass. This is done using a shape factor that relates the fragment impact area to its mass. Unfortunately, when a fragment impacts a witness plate, the hole area created is larger than the fragment projected area. The hole area is function of the projectile mass, velocity, shape and material properties. Therefore, the relationship between the witness plate hole area (A_h) and the fragment area (A_f) must be determined in order to characterize the fragment mass. The ratio (A_h/A_f) is referred to Hole Growth. Based on the model developed in this memorandum, estimates of this ratio for BA characterization and modeling is possible.

Experimental trials were conducted at DRDC Valcartier laboratories to develop a hole growth model for thin aluminium-1100 witness plate. Different projectile sizes have been used. Fragment Simulating Projectiles (FSP) weighting 0.24 g, 1.1 g, 2.85 g, and 4.15 g were chosen for the experimental tests and their characteristics are presented in Table 1. The FSP were fired on a 4-plate witness pack separated by 25 mm sheets of polystyrene foam. However, only the first plate was used for hole growth calculation. The plate was 1mm thick and made of aluminium 1100. Therefore, after experimental trials, the first plate of each set was analyzed with the Witness Pack Analysis System (WPAS), which labels each hole and calculates the corresponding area and position.

Table 1. FSP Description

MASS (g)	DIAMETER (D) (mm)	LENGTH (L) / DIAMETER (D) L/D
0.24	3.25	1.12
1.1	5.51	1.15
2.85	7.52	1.09
4.15	8.73	1.01

Additional experimental data from V50 tests were added to the data of Figure 1 and are shown in Figure 2. About 80 shots were performed to collect these data. The 1.1 g FSP A_h/A_f data variation versus velocity could be explained by the FSP instability while fired. Indeed, the barrel used to fire the 1.10 g FSP was old and worn and did not allow a straight trajectory before impacting the target. This can change the hole area produced by the projectile impacting the witness plate by changing its impact angle. The largest variations were observed for 1.1 g and 4.15 g FSP at a velocity close to their related V50 (104 m/s for 1.1 g and 64 m/s for 4.15 g).

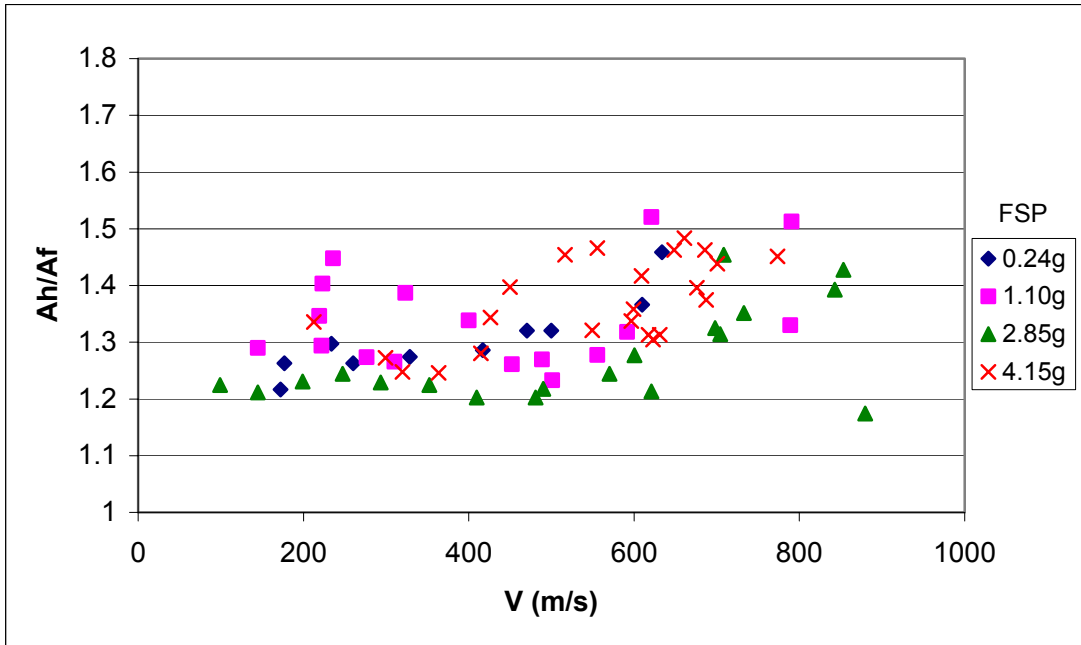


Figure 1. A_h/A_f versus velocity

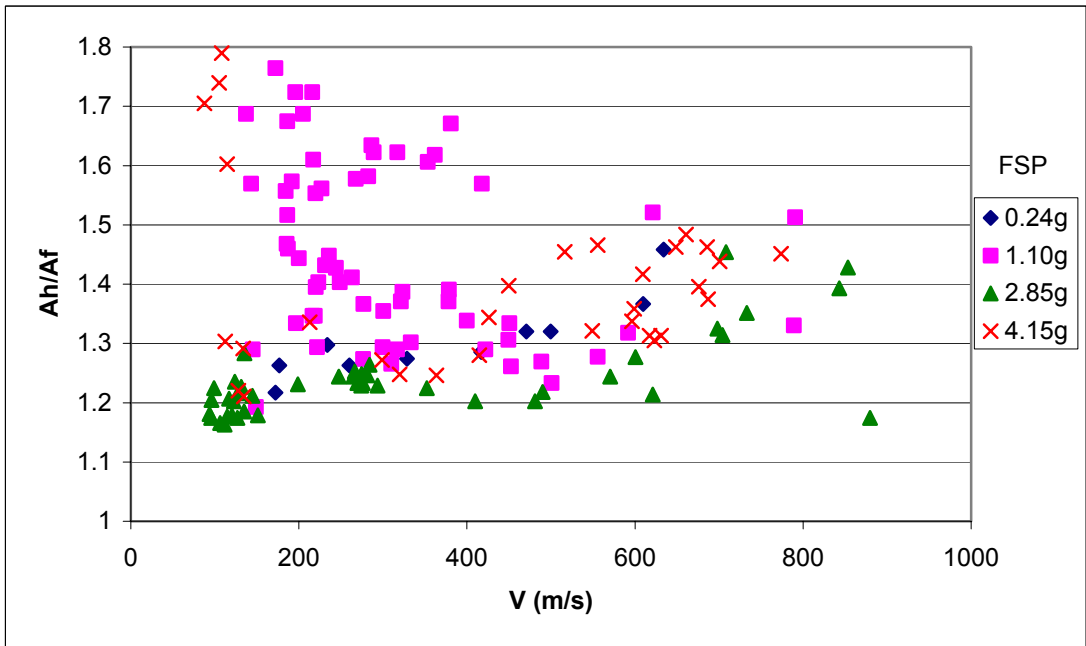


Figure 2. A_h/A_f versus velocity including V50 trials

Despite the fact that other models include fragment mass as a relevant parameter in the evaluation of the hole growth, the data presented in Figures 1 and 2 do not show this behaviour. Perhaps the fragment mass range is too small and experimental trials with higher fragment mass would show some changes with this parameter. A comparison will be made in following sections with some of the existing models to make some predictions for higher fragment mass.

A linear model using the impact velocity as the independent variable is presented in Figure 3 with the same experimental data as in Figure 1. The data collected for the ballistic limit (i.e. extra data presented in Figure 2) were not used to develop a model since the low velocity shots did not provide accurate values for hole area measured on the WP. This could be explained by the way the projectile penetrates the target at the velocity limit (V50). Indeed, the latter does not penetrate the target the same way it does for higher velocities. The crack does not appear right at the center point of impact and the resulting asymmetry is responsible for the FSP deviation. This deviation is clearly illustrated for the 1.10 FSP fired near the ballistic limit (Figure 2).

Equation (3) gives the hole growth ratio A_h/A_f versus velocity. Velocities range from about 100 up to 900 m/s. One should notice that fragment mass is not a parameter in this equation. Figure 4 presents the model accuracy by plotting A_h/A_f calculated with equation (3) versus A_h/A_f measured with the WPAS and the real projected FSP area.

$$A_h / A_f = 0.0002v + 1.2296 \quad (3)$$

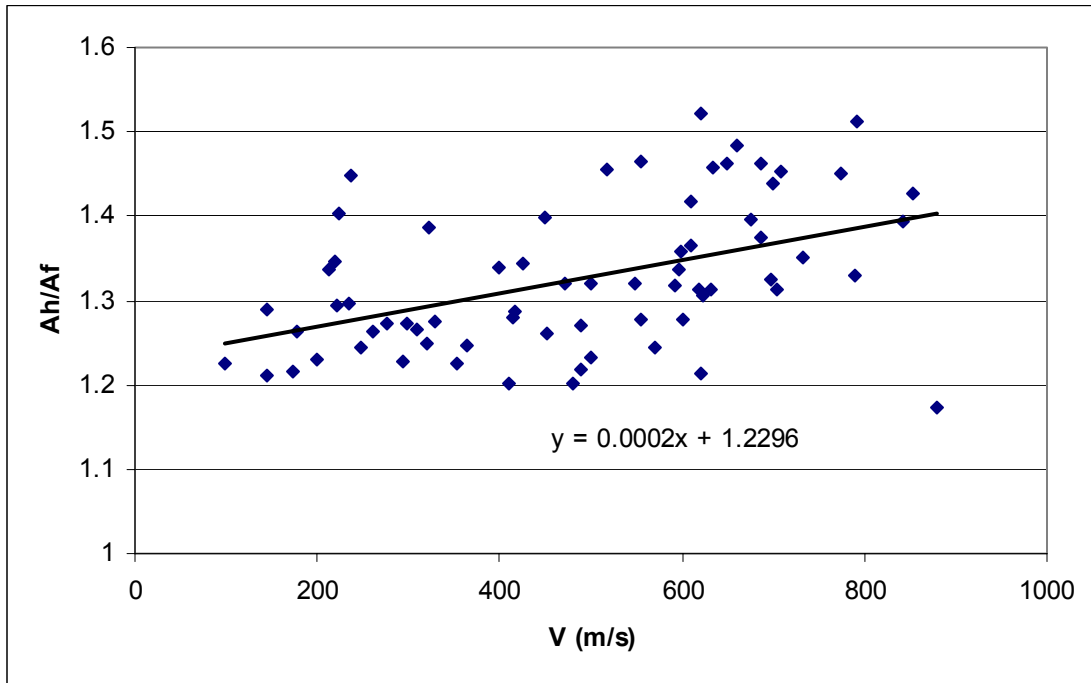


Figure 3. Linear model

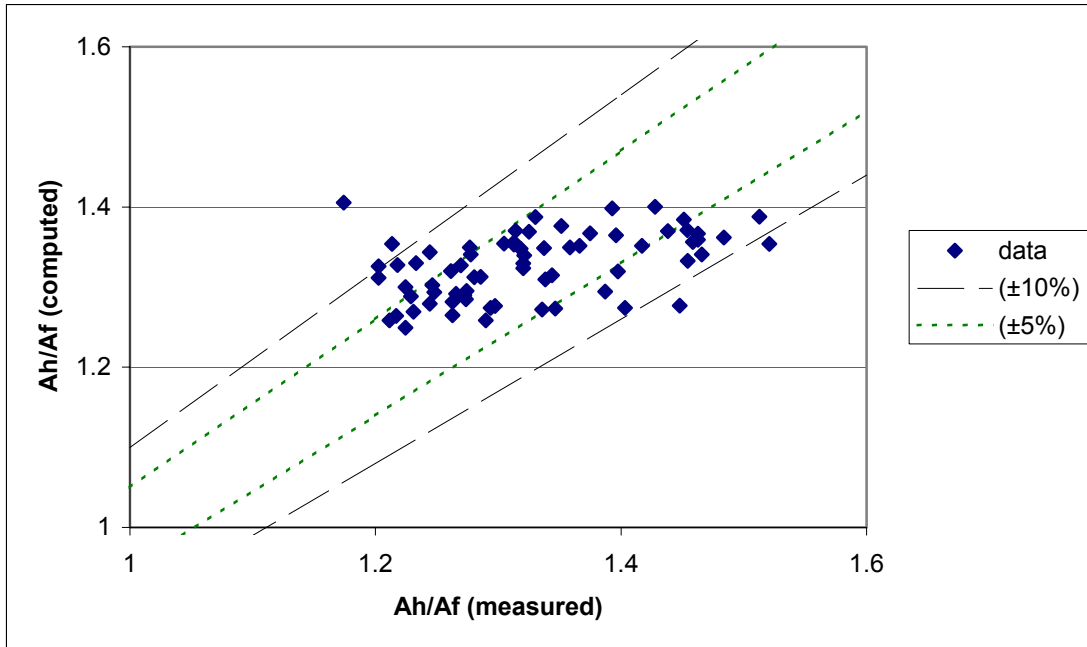


Figure 4. Linear model accuracy

As seen in Figures 3 and 4 there are a lot of variations in experimental results that cause some data to be out of the $\pm 10\%$ boundary. Again this variation might have been partially caused by projectile instability in flight.

2.1 Yatteau's model

Other models can be used for comparison and for testing the validity of the linear model. However, those models are generally valid for high velocity penetration while the linear model is valid in a low velocity range. Figure 5 presents D_h/D_f ratio versus velocity computed with Yatteau's Model [4] for the same experimental values used in the linear model. Fragment mass is a relevant parameter in Yatteau's model. This model (Equation 4) is based on the fragment and hole diameters and includes the witness plate thickness (T) as a parameter to calculate hole growth. Yatteau model gives the ratio D_h/D_f as a function of velocity. The constant h and k are empirical constants dependent on plate material ($h = 1.05$ and $k = 0.67$ for aluminium target) and M_f is the fragment mass. According to Figure 5, smaller fragment diameters gives higher D_h/D_f ratio. Yatteau's model also shows a linear relation for hole growth versus velocity. Moreover, the model designed for high velocity penetration is not very accurate for the given experimental data since the data do not fit in the 10% error range. Figure 6 shows that the error increases with FSP mass reduction.

$$D_h / D_f = 1 + \frac{(T / D_f)(M_f)^{1/3} [(3.02h + 0.0137kV^{2/3}) - 1]}{1.5} \quad (4)$$

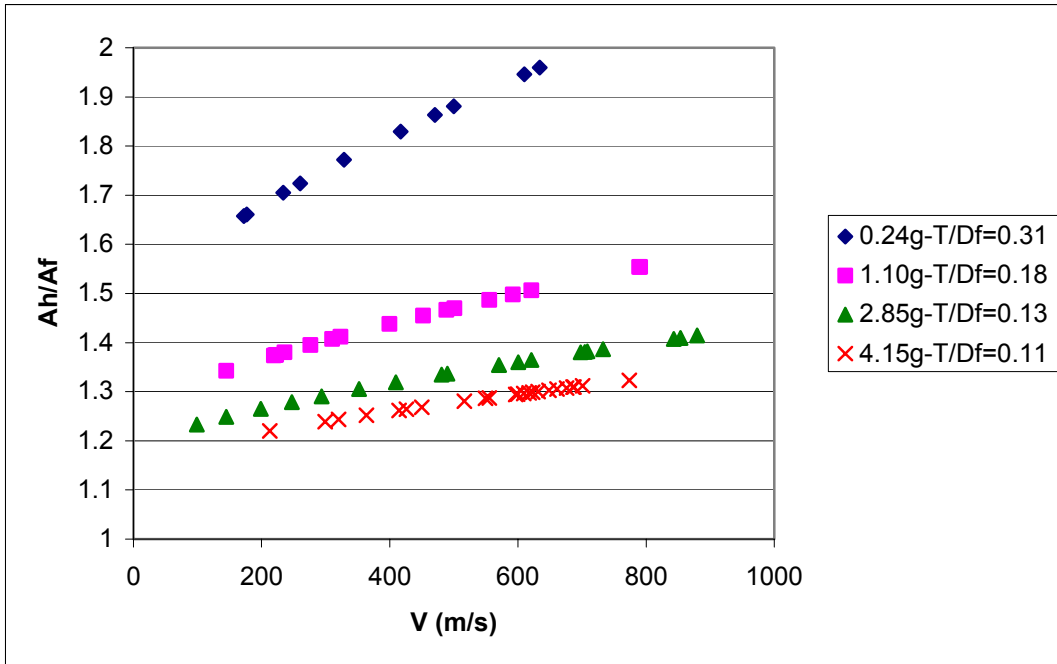


Figure 5. Yatteau's model

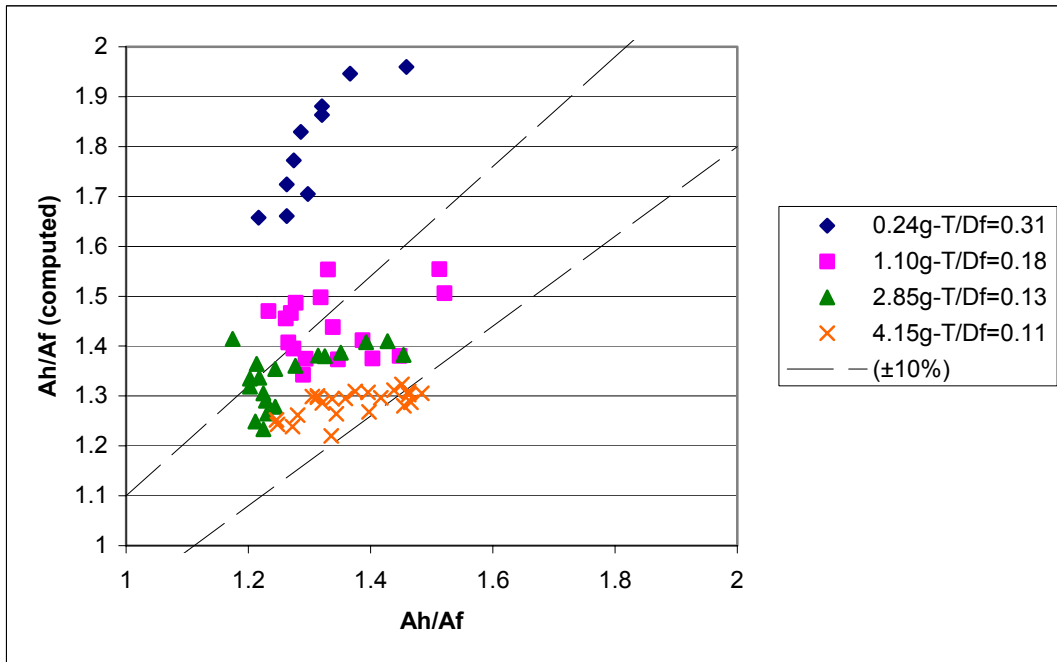


Figure 6. Yatteau's model accuracy

2.2 Combination of linear and Yatteau models

It would be interesting to apply the linear model for larger fragments. Figure 7 presents a combination of the linear and Yatteau models that will allow to compute the hole growth ratio for larger fragment masses up to 55 g. A 20 mm diameter fragment of 55 g has been used to derive this new model. The 2.85 g FSP was used for this extrapolation because its experimental data are the closest to the linear model line in Figure 3. Thus, the 2.85 g FSP line in Figure 7 corresponds to the linear equation (Equation 3) since the linear model does not include fragment mass. Thereafter, an extrapolation was performed between the hole growth ratio computed with the linear model for a 2.85 g fragment and the ratio computed with Yatteau's model for a 55 g fragment. Equation (5) allows computing the hole growth ratio based on the new model and can be used for steel fragment masses up to 55 g impacting an aluminium target. This new model includes fragment mass as a parameter.

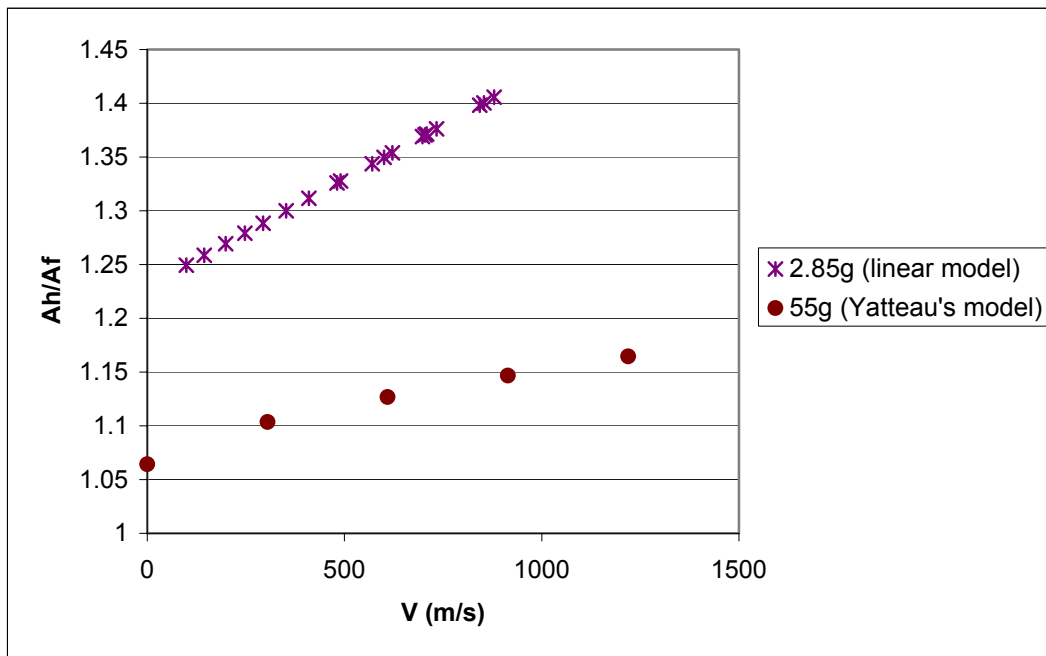


Figure 7. Combination of Linear and Yatteau's model

$$Ah / Af = (-0.000002m + 0.0002)v - 0.003m + 1.2382 \quad (5)$$

Figure 8 presents curves for different fragment masses based on the new model. In order to verify the accuracy of this model, eleven additional experimental tests were performed with a 20 mm FPS (53.78 g). In Figure 8, the linearity of the relationship between Ah/Af ratio and velocity is verified and the effect of the projectile mass on the ratio Ah/Af is confirmed with these experimental data. Finally, accuracy for the new model is presented in Figure 9. The error between experimental values and theoretical values is about $\pm 10\%$.

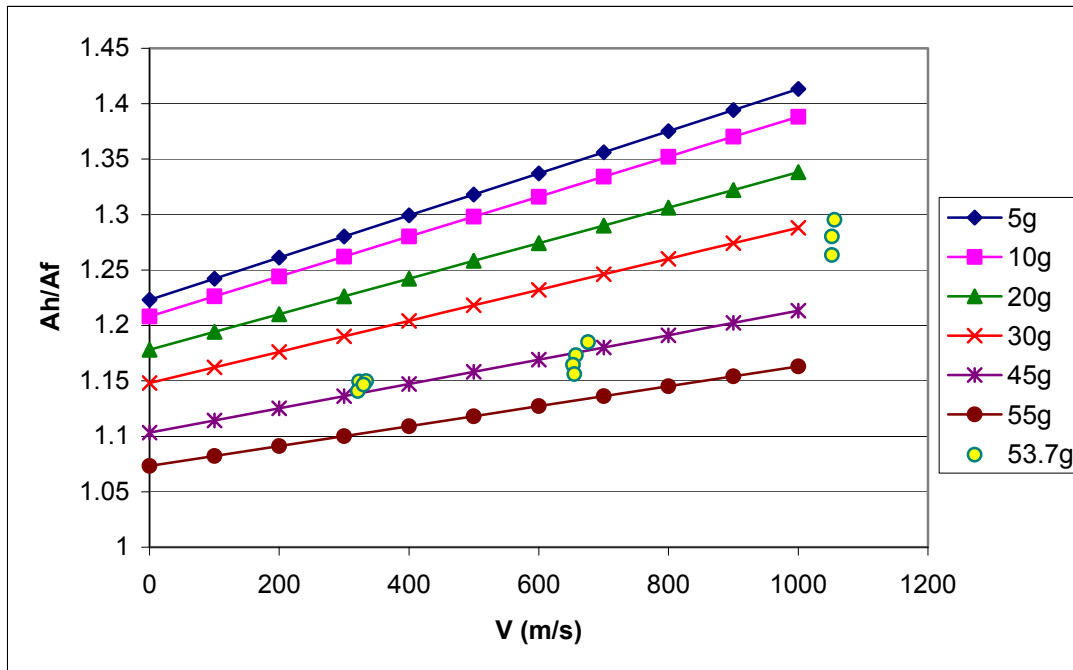


Figure 8. Hole growth versus velocity

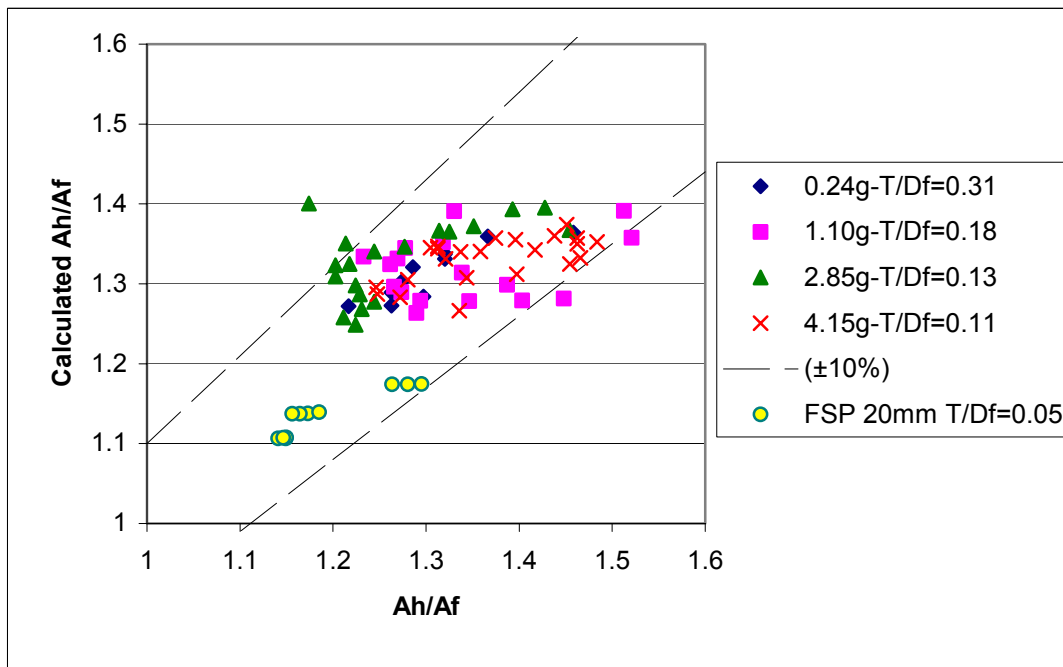


Figure 9. Model accuracy

2.3 Maiden's model

Another existing empirical model for high velocity penetration is Maiden's model [5]. This model requires sound velocity in the target material, target plate thickness and projectile diameter in order to compute Dh/Df ratio. Figures 10 and 11 present the area ratio versus velocity for experimental data and model accuracy, respectively. The model does not give accurate ratios for low velocity penetration (extrapolation) and give below unity ratio for those small velocities. Dh/Df ratio is computed according to Equation (6) and V_s is sound velocity in aluminium 1100 (6300 m/s).

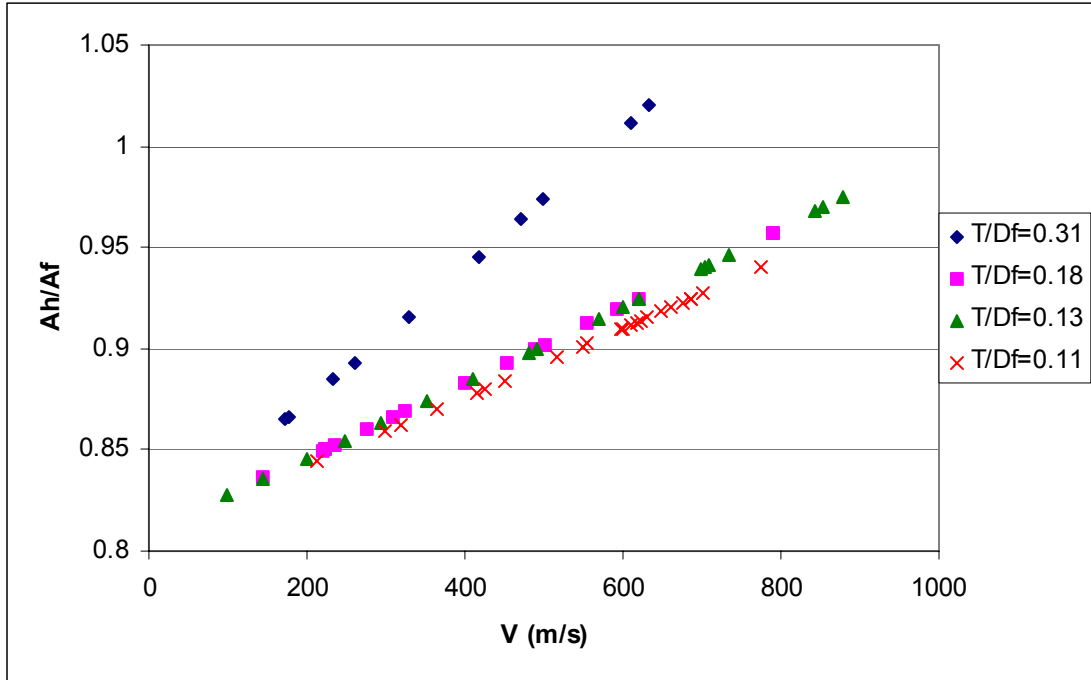


Figure 10. Maiden's model

$$Dh/Df = \left(2.4 \frac{v}{V_s} \right) \left(\frac{1}{Df} \right)^{2/3} + 0.9 \quad (6)$$

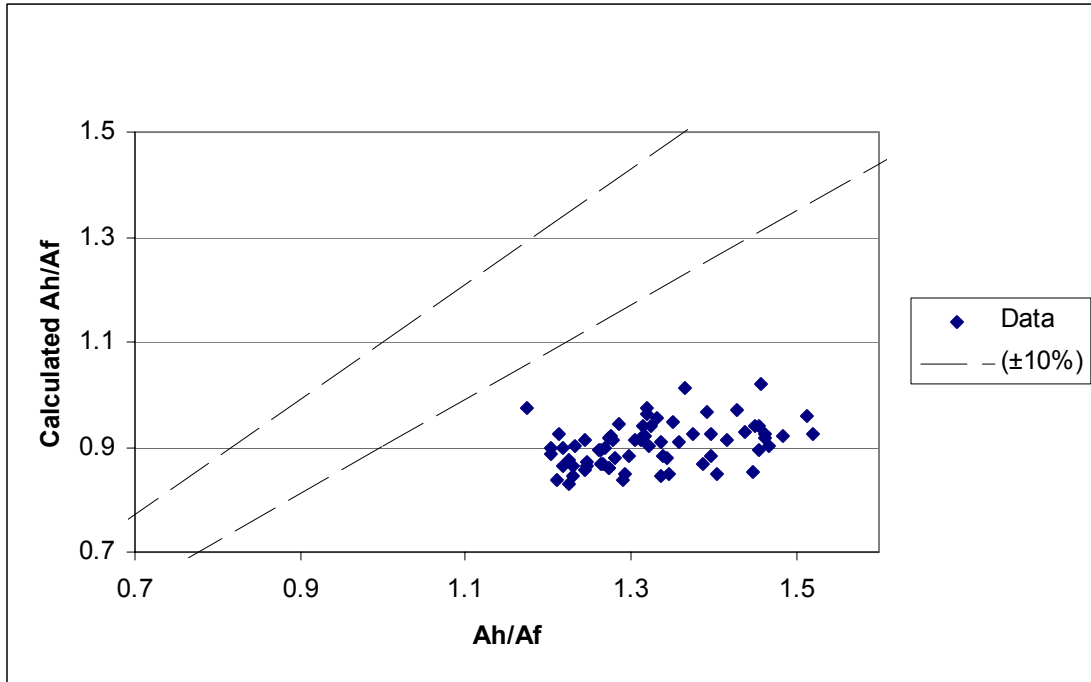


Figure 11. Maiden's model accuracy

2.4 VTC curves

Now that the hole growth ratio versus velocity can be computed, the objective is to obtain fragment mass and velocity estimates. Experimentally developed Velocity Threshold Curves (VTC) can be used with hole growth equations to achieve the desired witness pack characterization accuracy improvement. A new VTC equation (see Equation 7) was developed by DRDC Valcartier based on experimental data from Velrome et al. [6] and from V_{50} tests presented in Figure 2. Figures 12 and 13 present these new VTC for 3 plates of Al-1100 and Al-2024, respectively. Plate characteristics are presented in Table 2. Table 3 presents the constants used for the two different witness packs in Equation 7. An iterative process is required [7] to estimate fragment mass based on VTC curves and hole growth equations. However, this will not be discussed in this memorandum.

$$V_{50} = \frac{[b - a(\text{mass} + e)^c]}{(\text{mass} + e)^2} + d \quad (7)$$

Figures 13 and 14 clearly show that Al-1100 is perforated at lower velocity than Al-2024. For vulnerability/lethality analysis, the higher sensitivity offered by Al-1100 allows a better link to crewmembers injuries. Also, Al-1100 plates can be bought at a lower cost than Al-2024 plates.

Table 2. Plate characteristics

PLATE NO.							
PACK ID	1	2	3	4	5	6	7
	1mm Al	1mm Al	3 mm Al	1.5 mm St	1.5 mm St	1.5 mm St	1.5 mm St
	Al 1100 or Al 2024	Al 1100 or Al 2024	Al 1100 or Al 2024	St 1020	St 1020	St 1020	St 1020

Table 3. VTC constants

	a	b	c	d	e
AL-2024-T3					
PLATE 1	-503.799	128.662	1.964	-363.571	1.070
PLATE 2	-662.210	262.077	1.969	-483.759	1.080
PLATE 3	13419	14006	-0.072	172.882	1.157
AL 1100					
PLATE 1	-7516.535	295.455	1.999	-7440.217	1.586
PLATE 2	-4030.817	964.710	1.996	-3912.854	2.271
PLATE 3	-4113	980	2	-3834	2

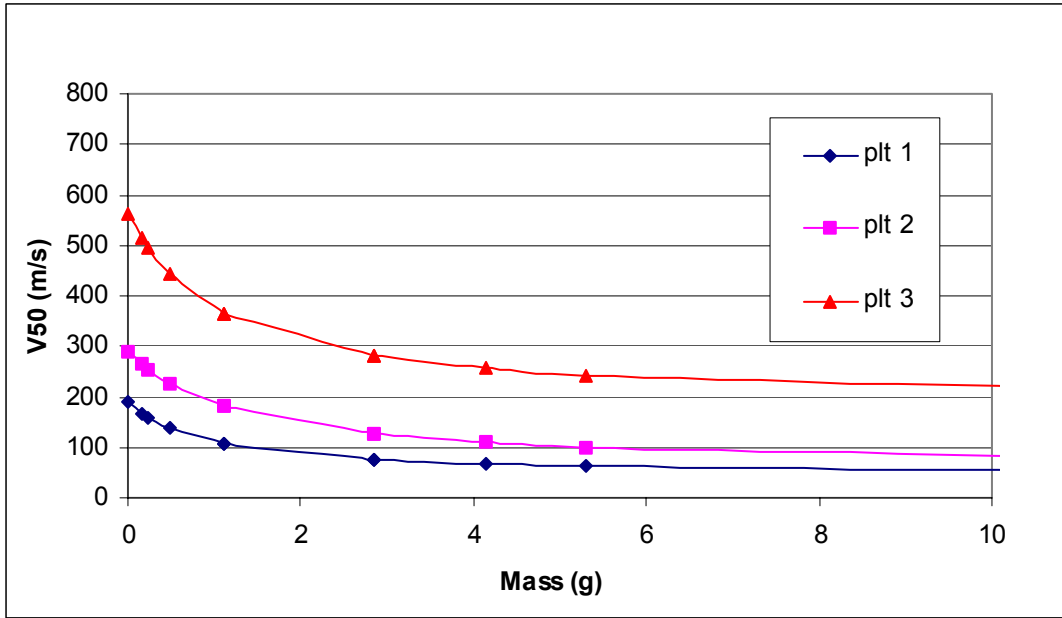


Figure 12. Velocity Threshold Curves for Al-1100

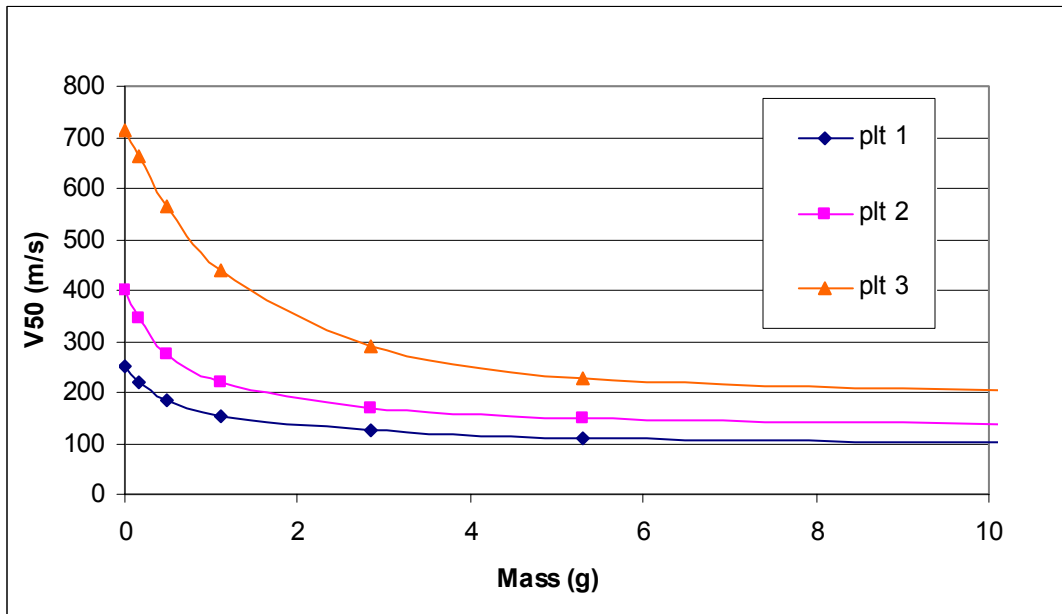


Figure 13. Velocity Threshold Curves for Al-2024

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3. Conclusion

This memorandum presents a model to compute hole growth as a function of fragment velocity for aluminium 1100 plate targets. Future application of the model will lead to an improved behind-armour debris characterization. However, this model is only valid for FSP smaller than 55g and fired at low velocities (from about 100 up to 900 m/s). For fragments larger than 55g, the hole growth ratio could be set at one.

Different models were presented and their accuracy verified with experimental data. The witness plate hole area is a function of the projectile velocity and its mass. Indeed, the heavier fragments have a smaller A_h/A_f ratio than the lighter fragments. The relationship between hole growth and velocity also proved to be linear in this study, except when the projectile velocity is close to the V50. It was also observed that there is an increase of the witness plate hole area (A_h) for increasing velocities.

Within the high velocity penetration model, Yatteau's model proved to be the most efficient. Therefore, an extrapolation was performed to adapt this model for low velocity penetration of heavier fragments. The resulting model includes fragment mass as a parameter for computing the A_h/A_f ratio versus velocity. Additional tests will have to be performed to confirm the accuracy of this assessment on a wider range of fragment mass.

Finally, VTC curves were presented for the 7 witness plates. It will be possible to estimate fragment mass and velocity with those curves and the hole growth equation developed in this memorandum.

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List of symbols/abbreviations/acronyms/initialisms

DND	Department of National Defence
Af	Projected fragment area (section area)
Ah	Projected hole area on witness plate
BA	Behing-Armour
DeCaM	Debris Characterization and Modelling Software
Df	Fragment diameter
Dh	Hole diameter
DRDC	Defense R&D Canada
FSP	Fragment Simulating Projectile
h	Constant (equation 4)
Mf	Fragment mass
k	Constant (equation 4)
T	Target plate thickness
Vs	Sound velocity in target material
VTC	Velocity threshold curves
V50	Velocity limit
WPAS	Witness Pack Analysis System
WP	Witness Pack

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(U) Behind-Armour (BA) debris generated after ballistic penetration events are recognized as being of major importance in vulnerability/lethality assessment. There are some constraints affecting characterization and modelling of these BA debris. One of those constraints is resolved in this memorandum by developing a mathematical model that will increase the accuracy of the fragment mass and velocity estimates of fragment impacting aluminium-1100 witness plates. The objective of the model is to define the hole growth ratio of the perforated hole area (Ah) on the first witness plate versus the fragment projected area (Af).

(U) Experimental trials were conducted with Fragment Simulating Projectiles (FSP) of different sizes. The mathematical model developed is then based on those experimental data. The analyses were performed with the latest versions of DeCaM (Debris Characterization and Modelling software) and WPAS (Witness Pack Analysis System). These analysis systems were developed at DRDC Valcartier. Experimental results show a linear relationship between hole growth ratio and velocity. Therefore, a linear model was developed to compute this Ah/Af ratio. Other existing models were applied to experimental data to verify their validity. In this particular case, Yatteau's model developed for high velocity penetration revealed to be the most accurate with the experimental data and was combined to the developed model to perform extrapolation. The hole growth equation and the Velocity Threshold Curves (VTC) presented in this memorandum will allow further characterization of BA effects.

14. MOTS-CLÉS, DESCRIPTEURS OU RENSEIGNEMENTS SPÉCIAUX (Expressions ou mots significatifs du point de vue technique, qui caractérisent un document et peuvent aider à le cataloguer. Il faut choisir des termes qui n'exigent pas de cote de sécurité. Des renseignements tels que le modèle de l'équipement, la marque de fabrique, le nom de code du projet militaire, la situation géographique, peuvent servir de mots-clés. Si possible, on doit choisir des mots-clés d'un thésaurus, par exemple le "Thesaurus of Engineering and Scientific Terms (TESTS)". Nommer ce thésaurus. Si l'on ne peut pas trouver de termes non classifiés, il faut indiquer la classification de chaque terme comme on le fait avec le titre.)

Hole growth, fragment, hole area, witness pack, witness plate, fragment mass, fragment velocity, behind-armor, FSP, behind-armour.

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