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PROBABILISTIC MODELING OF INITIATION DUE TO FRAGMENT IMPACT

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ABSTRACT

A probabilistic analytic model of initiation for the STANAG 4496 Insensitive Munitions (IM) Fragment Impact (FI) test was developed. The deterministic Jacobs-Roslund (JR) detonation initiation model was augmented to include impact point offset and fragment tilt against a curved munition case. This augmentation was based on geometrical aspects of the impact and the shock produced by impact. The model was calibrated using the 1-D hydrocode, GODLAG. The velocities and thicknesses of the 1-D GODLAG impactors were calibrated based on matching peak pressures and pressure histories from previous fully 3-D fragment impact hydrocode modeling using a 155mm diameter munition configuration. A state of the art probability tool was subsequently used for variational impact conditions using the newly developed analytic IM FI explosive initiation model. The probability computational program AgenaRisk was used. AgenaRisk is a Bayesian Belief Network (BBN) implementation and computes probabilistic relationships. Each variable, or node, is given a certain probability distribution. By expressing the mutual dependencies of the different variables, probabilistic computations are made. By implementing the augmented JR model in AgenaRisk, a probabilistic initiation response model was obtained. A test case was run using the same 155mm diameter munition configuration that was used for the model calibration. The varied parameters included the fragment velocity, tilt and impact position offset. The results showed a large reduction in initiation probability can occur as a result of impact position offset and fragment tilt.

Keywords:

Fragment, Initiation, Probability, Modelling.

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ABBREVIATIONS

BBN	Bayesian Belief Network
FI	Fragment Impact
GODLAG	Godunov One-Dimensional LaGrangian Hydrocode
IM	Insensitive Munitions
JR	Jacobs-Roslund
KMA	Royal Netherlands Military Academy
MSIAC	Munitions Safety Information Analysis Center
NATO	North Atlantic Treaty Organization
PIMS	Particle Impact Mitigation Sleeve
STANAG	Standardization Agreement
TEMPER	Toolbox of Engineering Models to Predict Explosive Reactions

INTRODUCTION

Insensitive Munitions (IM) fragment impact testing is commonly conducted as specified in NATO STANAG 4496 [1] and AOP-4496 [2]. Figure 1 shows a typical gun test setup used for fragment impact testing. Normally, the test item is essentially placed as close to the gun as possible without causing damage to the gun. This is done in order to reduce impact variability. Typical distance from the gun is 6 to 10 meters. The standard has several loosely defined and undefined characteristics that can affect the test item response. In particular, fragment velocity variation, impact point variation, and fragment tilt upon impact are commonly observed. The effects of these variations have been largely unknown and unquantified.

AOP-4496 specifies a standard fragment (projectile) geometry, a standard fragment velocity of 2530±90 m/s, and an alternate fragment velocity of 1830±60 m/s. A fragment tilt of within 10° is suggested and no impact point tolerance is specified. Figure 2 presents a drawing of the NATO standard fragment and Figure 3 schematizes these sources of variation. The red fragment impacts a warhead, consisting of three layers, with various tilted and off-center fragment orientations relative to the target. This is, from here on, referred to as tilted and off-center impacts. Baker et al. [3] have shown through 3-D simulations that the peak pressure measured in the explosive differs significantly for tilted and off-center hits. Currently these variations are not taken into account. The existing Jacobs-Roslund deterministic initiation model estimates the critical impact velocity above which explosive initiation will occur. It takes several fragment and warhead characteristics into account, but does not include fragment tilt or off-center impact. An analytic model has been developed that accounts for fragment tilt and off-center impact. This model was coupled to probabilistic software in order to do case studies. This report provides a shorter summary of the more complete MSIAC report [4] detailing the model development and case studies.

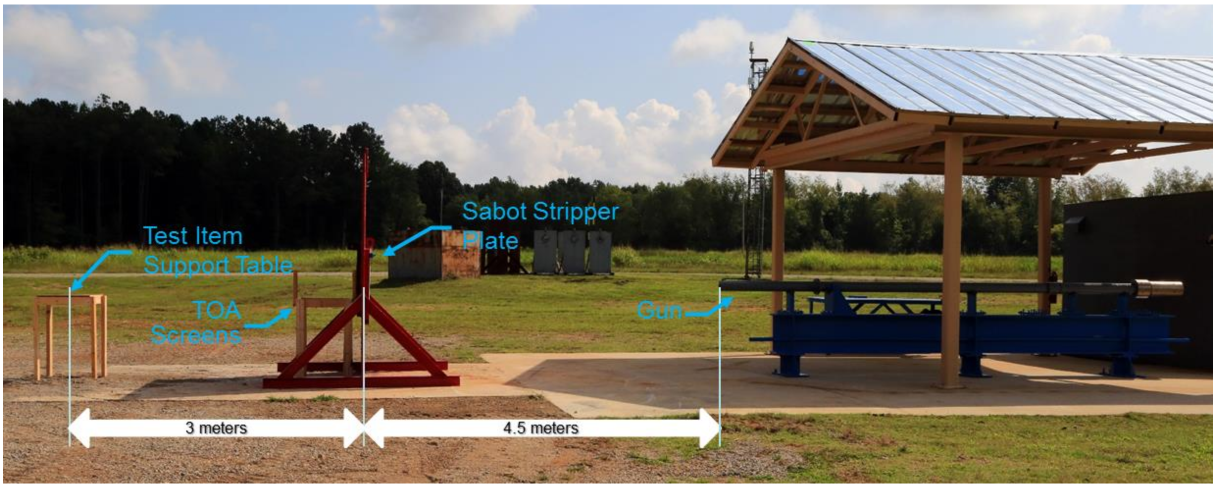


Figure 1. Typical test setup used for fragment impact testing (US Army Redstone Test Center).

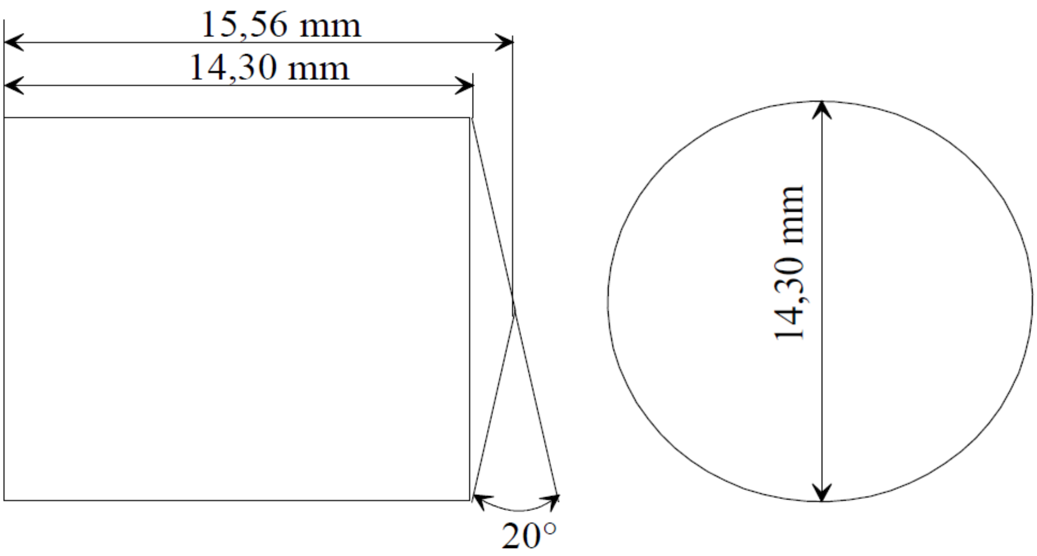


Figure 2. The NATO standard fragment [2].

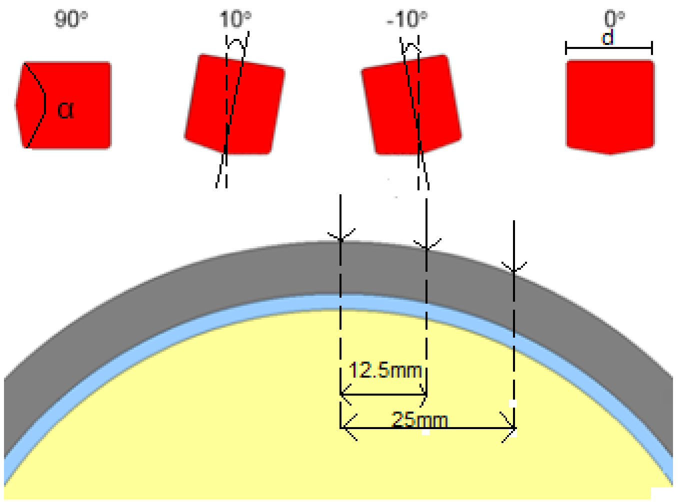


Figure 3. Schematized fragment (red) tilt and impact point variation [3].

1 DETERMINISTIC INITIATION MODEL DEVELOPMENT

1.1 JACOBS-ROSLUND INITIATION MODEL

The Jacobs-Roslund (JR) model [5] is a model that is used to simulate projectile impact on covered explosive configurations. It provides the critical impact velocity, $V_{Critical}$ of a fragment needed to detonate a warhead as a function of various fragment and warhead parameters. By comparing the fragment's impact velocity, V_{Impact} with $V_{Critical}$, the JR model predicts a 'detonation' or 'no detonation'. It is important to note that the JR model is deterministic. To calculate $V_{Critical}$, a limited set of parameters is used: fragment size and shape, explosive sensitivity, and warhead cover thickness The JR model is given in Eq. (1). Table 1 provides the corresponding definitions of the symbols used. Figure 4 presents a typical JR model critical velocity curve as a function of fragment velocity and fragment diameter.

$$V_{Critical} = \frac{A}{d^{0.5}} * (1 + B) * \left(1 + C\,\frac{t}{d}\right), \tag{1}$$

$$V_{Impact} < V_{Critical} : \text{No detonation}$$

$$V_{Impact} > V_{Critical} : \text{Detonation}$$

Table 1. Symbols and their definitions and units used in the JR model.

	Symbol	Definition	Unit
	$V_{Critical}$	Critical impact velocity for warhead detonation	[m/s]
Fragment	d	Fragment critical dimension or diameter	[m]
	B	Projectile shape coefficient	[-]
Warhead	t	Warhead cover thickness	[m]
	A	Explosive sensitivity coefficient	[$m^{3/2}$ s^{-1}]
	C	Cover plate protection coefficient	[-]

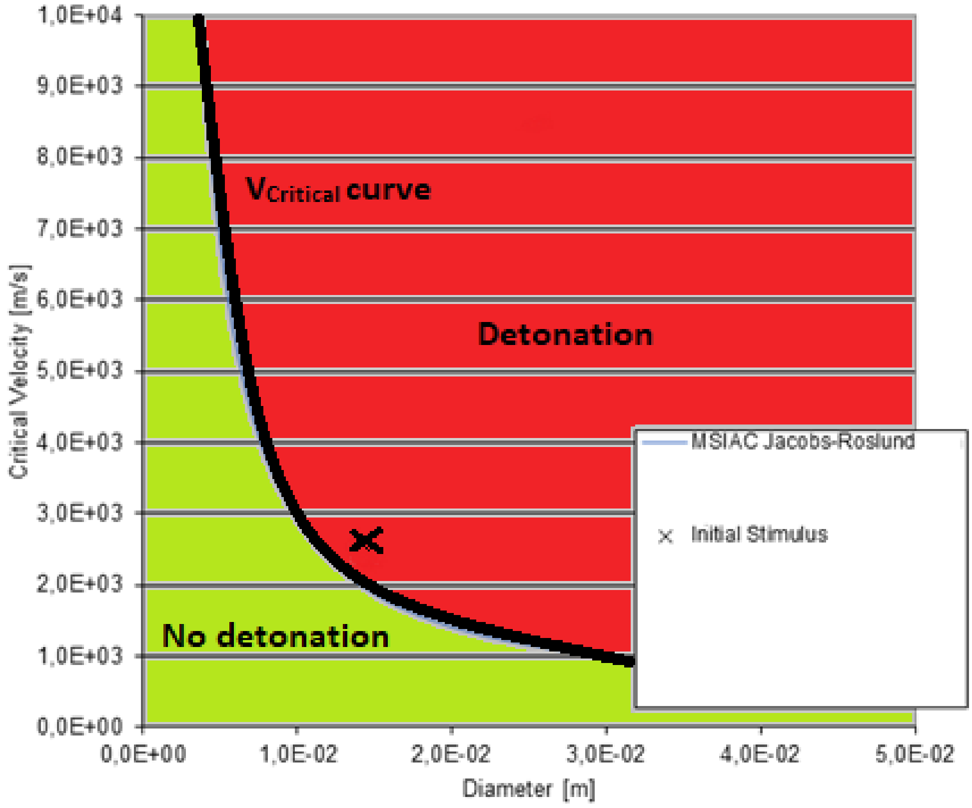
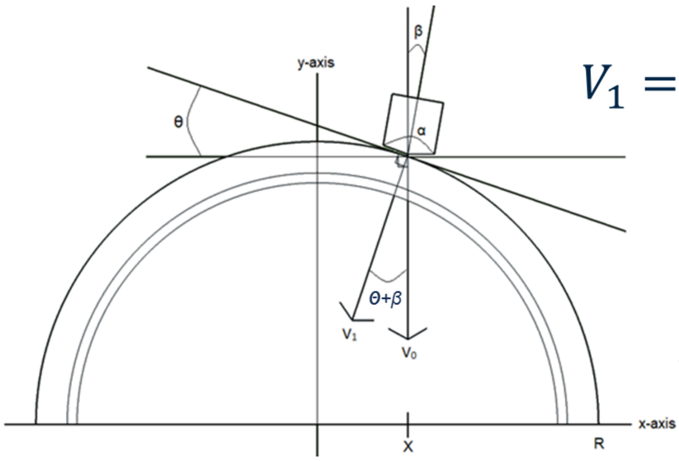


Figure 4. Example JR model critical velocity curve.

1.2 APPARENT VELOCITY CONCEPT

A modification of the JR model was developed to account for projectile tilt and off center impact. This model was developed around the idea calculating an apparent fragment impact velocity that accounted for the lower shock pressure produced from tilted and off-center impacts. The central idea of this reduced velocity is a geometric argument that calculated the apparent projectile velocity in the direction normal minus the tilt angle to the impact surface, the idea being that tilting into the surface will increase shock pressure and tilting away from the surface will decrease the shock pressure. Figure 5 presents a sketch depicting the geometry including the actual fragment velocity, V_0 and the apparent fragment velocity, V_1.



$$V_1 = V_0 * \cos(\theta + \beta) \quad (2)$$

$$\theta = \tan^{-1}\left(-\frac{X}{\sqrt{R^2 - X^2}}\right)$$

(β clockwise is negative)

Figure 5. Apparent velocity geometric depiction.

1.3 HYDROCODE CALCULATIONS

Baker et al. [3] conducted a computational fragment impact study using the 3-D CTH high rate continuum model. The study showed that velocity, tilt, and aim point variation affect the shock and pressure histories in the warhead explosive. Figure 3 shows the model set-up for this earlier research. The standard NATO fragment was impacted at 2530 m/s upon a 155mm diameter warhead. The warhead contains the explosive material PBXN-9 and has a steel casing. The simulations were conducted with and without a plastic internal particle impact mitigation sleeve (PIMS) [6]. Impact simulations were conducted with tilted fragments at 90°, 10°, 0° and -10° at 0mm, 12.5mm and 25mm off-center impacts. The resulting 3-D pressure history models for the 10° to -10° tilts were used to calibrate an apparent impactor velocity using the 1-D GODLAG hydrocode that is available in the MSIAC TEMPER tool [7]. Figure 6 shows the model set-up for the 1-D calculations. Table 2 presents the associated materials and model parameters.

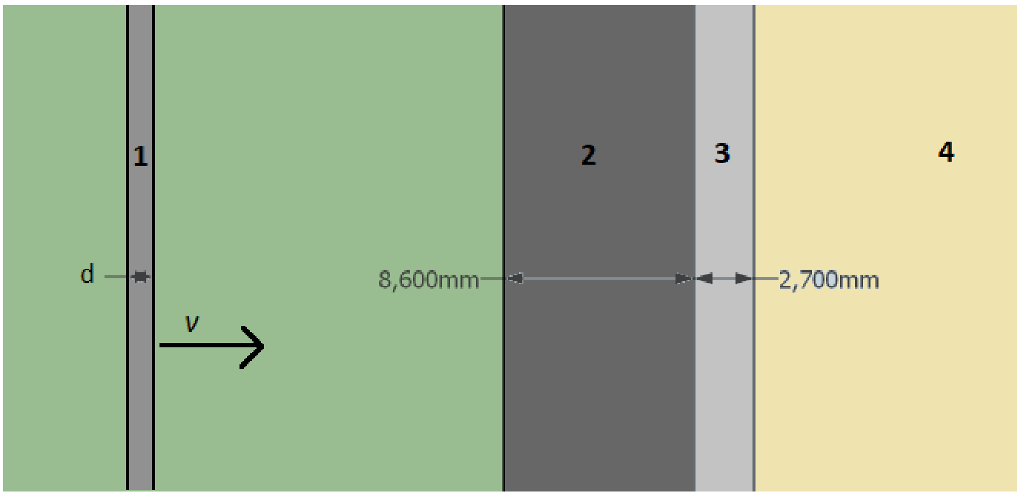


Figure 6. 1-D GODLAG modelling study set-up with PIMS.

Table 2. Materials and model parameters used in 1-D GODLAG modelling.

Material (numbers correspond with Figure 16)	ρ (density) [kg/m³]	C_0 (speed of sound) [m/s]	S (slope of Hugoniot) [m/s]	Γ (Grüneisen parameter) [-]
1. Steel (mild) NATO fragment	7550	4690	1.58	1.5
2. Steel (4340) cover warhead	7850	4570	1.49	1.93
3. PMMA layer (PIMS)	1182	2180	2.088	0.85
4. PBXN-9	1815	2320	2.21	1.1

The idea was to replicate the impactor pressure history of the NATO fragment that was calculated using the 3-D model by using the 1-D model. The thickness of the impactor in the 1-D model was adjusted so that the pressure history from a fragment with an impact velocity of 2530 m/s with 0° tilt and 0mm off-center from the 3-D model, matches the pressure characteristics of an impact in the 1-D model with the same velocity. This thinning of the 1-D impactor provides a similar rarefaction in 1-D as would be seen from the 3-D model, as the rarefaction occurs in the radial direction from the projectile edge in 3-D, whereas the rarefaction occurs from the impactor rear surface in 1-D. Figure 7 presents a comparison of the resulting 1-D and 3-D pressure histories using a 1-D chosen impactor thickness of 1.195mm. The histories are offset simply due to a different initial impact time. As can be seen, the histories match the initial shock pressure very closely and the resulting rarefactions quite closely.

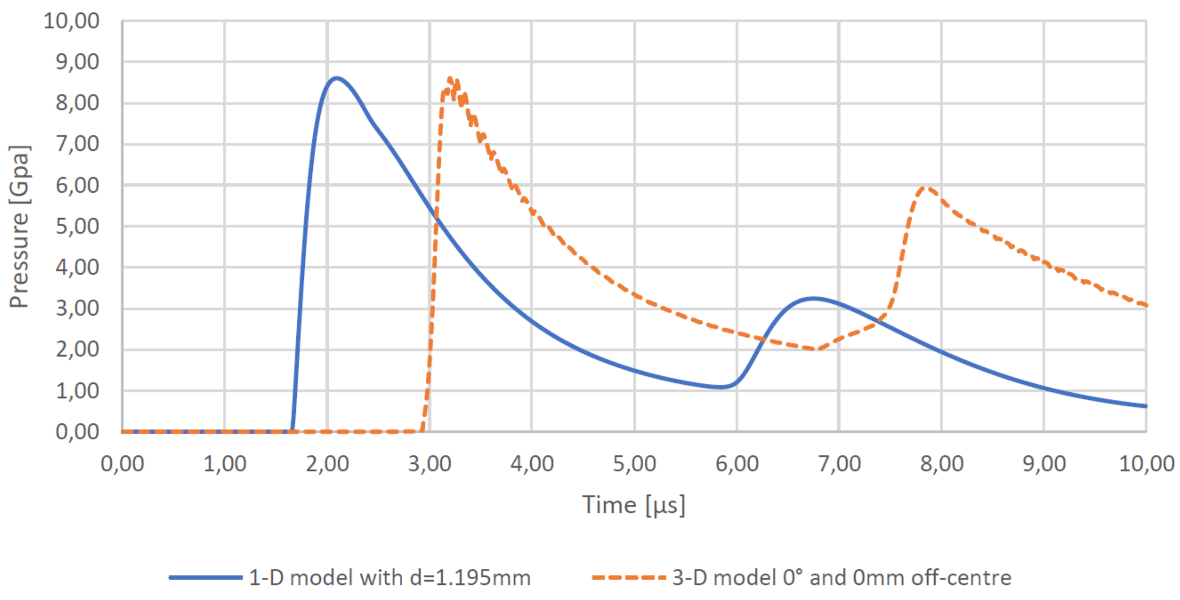


Figure 7. 3-D and 1 D model pressure histories with PIMS.

The process of determining the 1-D hydrocode impactor velocities was done by matching the maximum shock pressure in the high explosive. This was conducted for all reference fragment orientations. Figure 8 presents a comparison of the resulting 1-D and reference 3-D model maximum pressure histories for various -10° tilted impacts. As can be seen, the pressure histories match quite well. Table 8 provides a listing of all the 1-D reduced velocities corresponding with the 3-D reference maximum pressures.

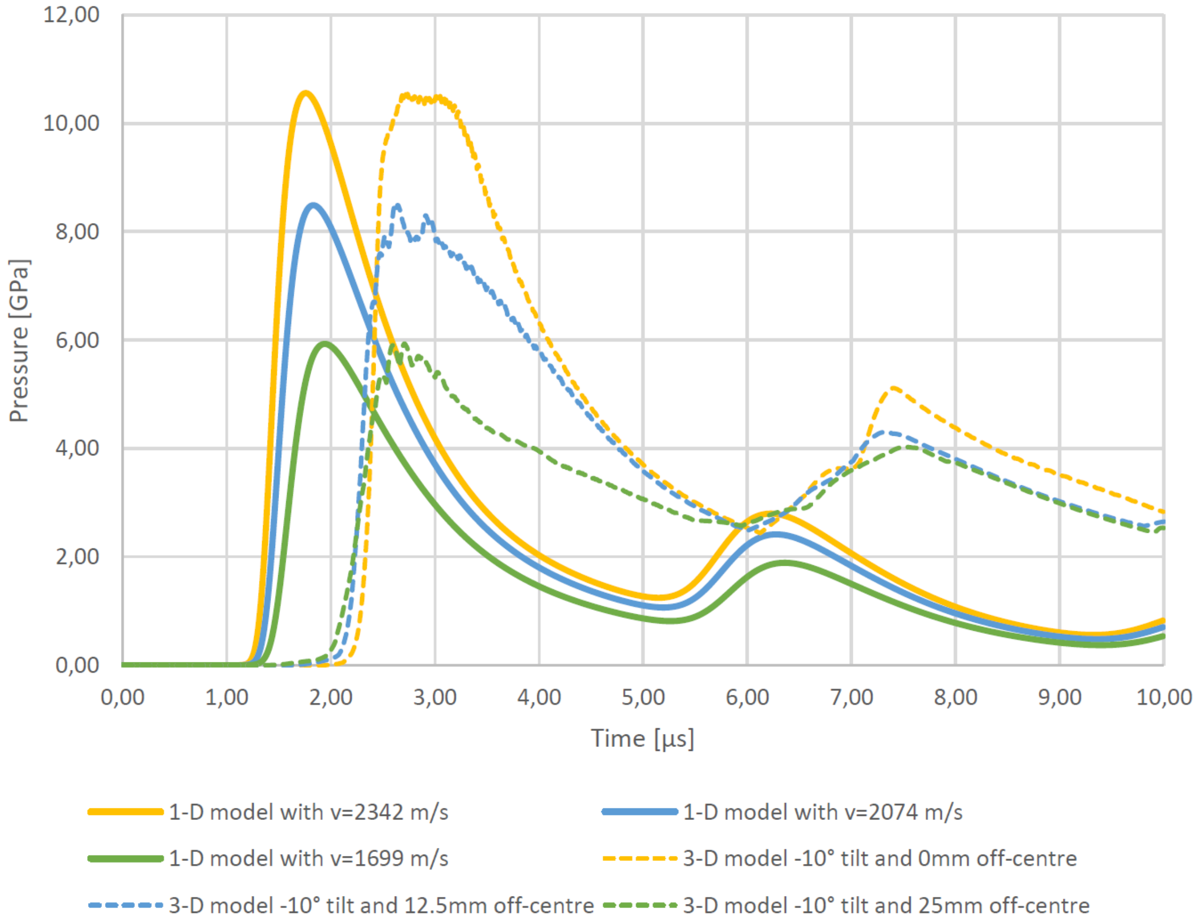


Figure 8. 1-D and 3-D pressure histories for -10° tilted impact without PIMS.

Table 3. 1-D reduced velocities corresponding with the reference pressures.

Fragment orientation Angle of tilt	off-centre	3-D model max pressure with PIMS (GPA)	Matching 1-D hydrocode velocity	3-D model max pressure without PIMS (GPa)	Matching 1-D hydrocode velocity
0°	0mm	8.60	2530	12.13	2530
0°	12.5mm	7.83	2410	11.18	2418
0°	25mm	5.46	2000	8.65	2096
10°	0mm	7.73	2394	10.75	2366
10°	12.5mm	8.36	2493	11.87	2500
10°	25mm	7.48	2354	11.04	2401
-10°	0mm	7.71	2391	10.56	2342
-10°	12.5mm	5.55	2016	8.49	2074
-10°	25mm	3.72	1634	5.30	1699

1.4 ANALYTIC MODEL VELOCITY CORRECTIONS

The geometrically derived apparent velocities are compared to the hydrocode derived reduced velocities in Figure 9.

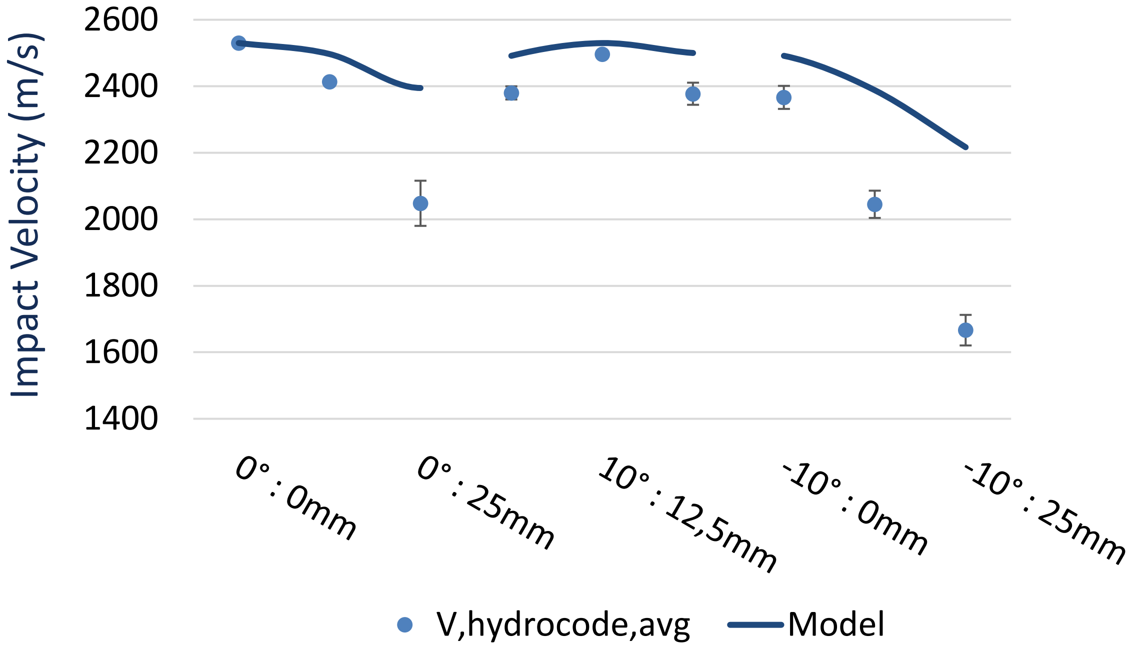


Figure 9. Geometrically derived apparent velocities compared to hydrocode derived velocities.

As can be seen from the figure, the geometrically derived apparent velocities follow the trend of the hydrocode derived impact velocities, but do not provide quantitative agreement. It is believed that this discrepancy is due to the fact that the geometrically derived apparent velocities do not account for the oblique nature of the shocks produced from the oblique impacts. Oblique shocks have significantly reduced shock pressures as compared to normal impacts. In order to account for this further reduction of shock pressure, the geometrically derived apparent velocities were further reduced using the apparent velocity correction per Eq. (3).

$$V_1 = V_0 * (\cos(\theta + \beta))^{\lambda} \tag{3}$$

The value of λ was then adjusted to a value of 3.822 in order to provide agreement with the hydrocode derived velocities as seen in Figure 10. As can be seen, the achieved agreement between the adjusted apparent velocities and the hydrocode derived velocities is quite good.

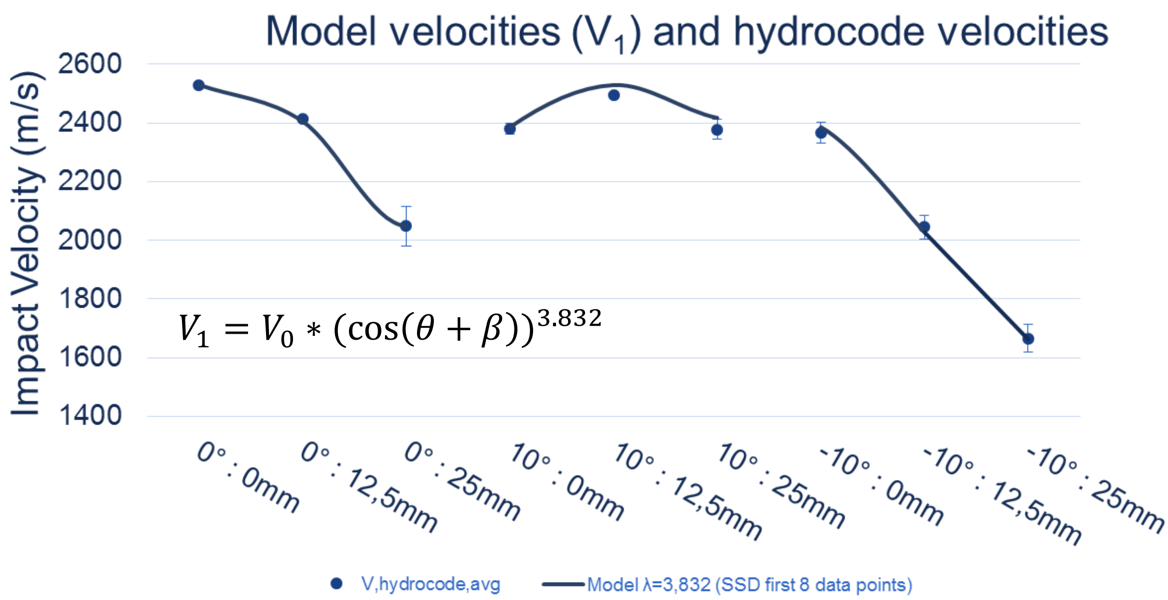


Figure 10. Adjusted apparent velocities compared to hydrocode derived velocities.

1.5 JACOBS-ROSLUND LEIBBRANDT MODEL

The apparent velocity was introduced into the JR model in order to account for the impact point offset and fragment tilt. The resulting "JR Leibbrandt" model for the critical velocity is given in Eq. 4. Table 4 provides the corresponding definitions of the symbols used.

$$V_{Critical} = \frac{A}{d^{0.5} * (\cos(\theta+\beta))^{\lambda}} * (1+B) * \left(1 + C\frac{t}{d}\right) \tag{4}$$

Table 4. JR Leibbrandt model symbols and their definitions and units.

	Symbol	Definition	Unit
	$V_{Critical}$	Critical impact velocity for warhead detonation	[m/s]
Fragment	d	Fragment critical dimension or diameter	[m]
	θ	Angle of tangent at impact point	[°]
	β	Fragment's angle of tilt	[°]
	λ	Leibbrandt-coefficient	[-]
	B	Projectile shape coefficient	[-]
Warhead	t	Warhead cover thickness	[mm]
	A	Explosive sensitivity coefficient	[$m^{3/2} s^{-1}$]
	C	Cover plate protection coefficient	[-]

Figures 11 and 12 present plots of the apparent velocity, Eq. (4), as a function of off-center distance and tilt angle, using an initial velocity, V_0, of 2530 m/s and a warhead radius of 155mm.

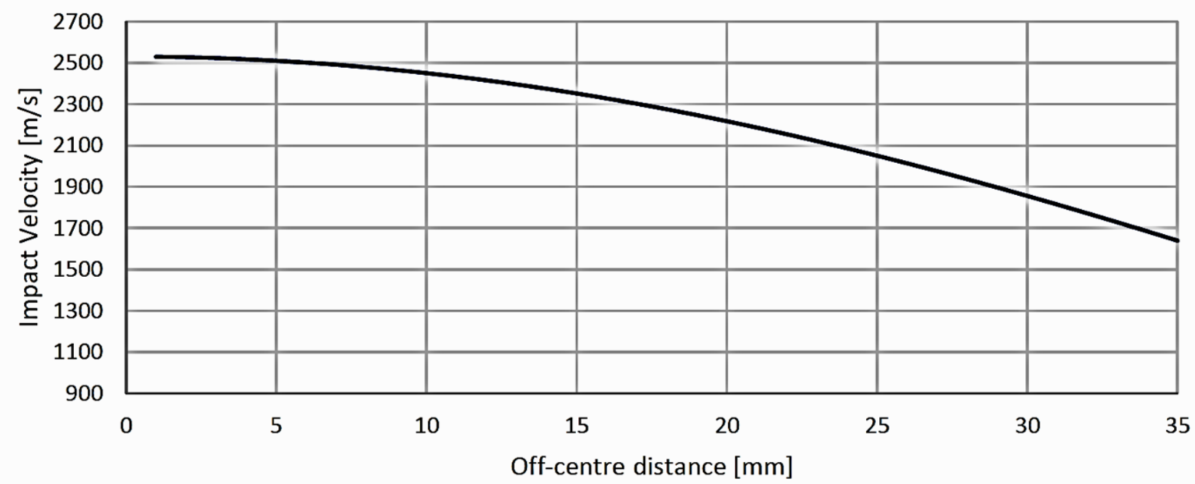


Figure 11. Reduced apparent impact velocities for off-center distance.

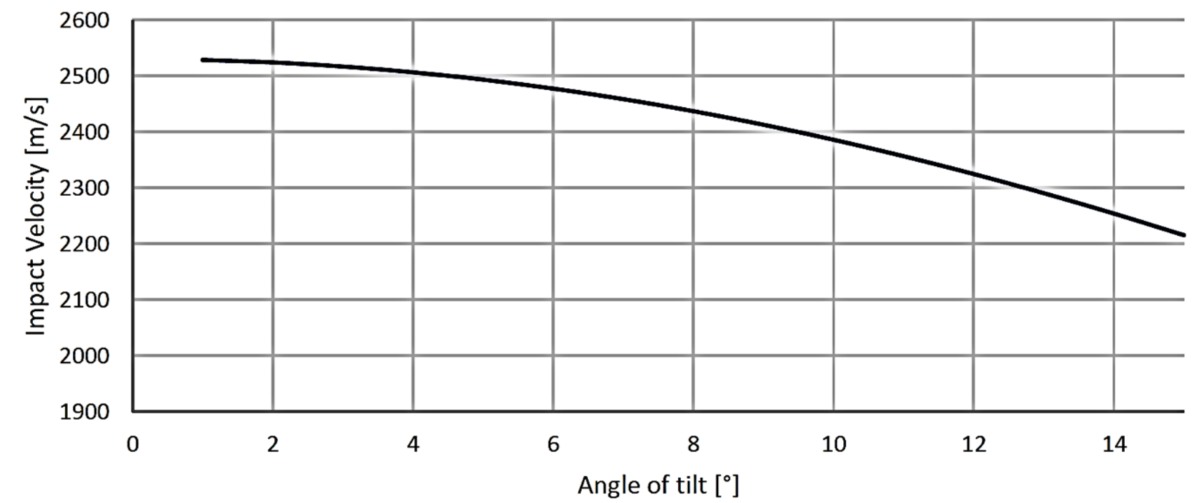


Figure 12. Reduced apparent impact velocities for angle of tilt.

2.1 BAYESIAN BELIEF NETWORK

In order to obtain a probabilistic initiation response model using the JR Leibbrandt model, the computational program “AgenaRisk” is used [8]. This program is a Bayesian Belief Network (BBN) and computes probabilistic relationships. Each variable, or node, is given a certain probability distribution. By expressing the mutual dependencies of the different variables, probabilistic computations can be made. By implementing the JR Leibbrandt model in AgenaRisk, a probabilistic initiation response model was obtained. Figure 13 presents a schematic example of a probabilistic initiation response model using the AgenaRisk BBN. Distribution functions are provided for the impact velocity, fragment tilt and impact point offset. AgenaRisk than does a BBN analysis using the mutual dependencies of the JR Leibbrandt model and predicts the probability of detonation and no detonation.

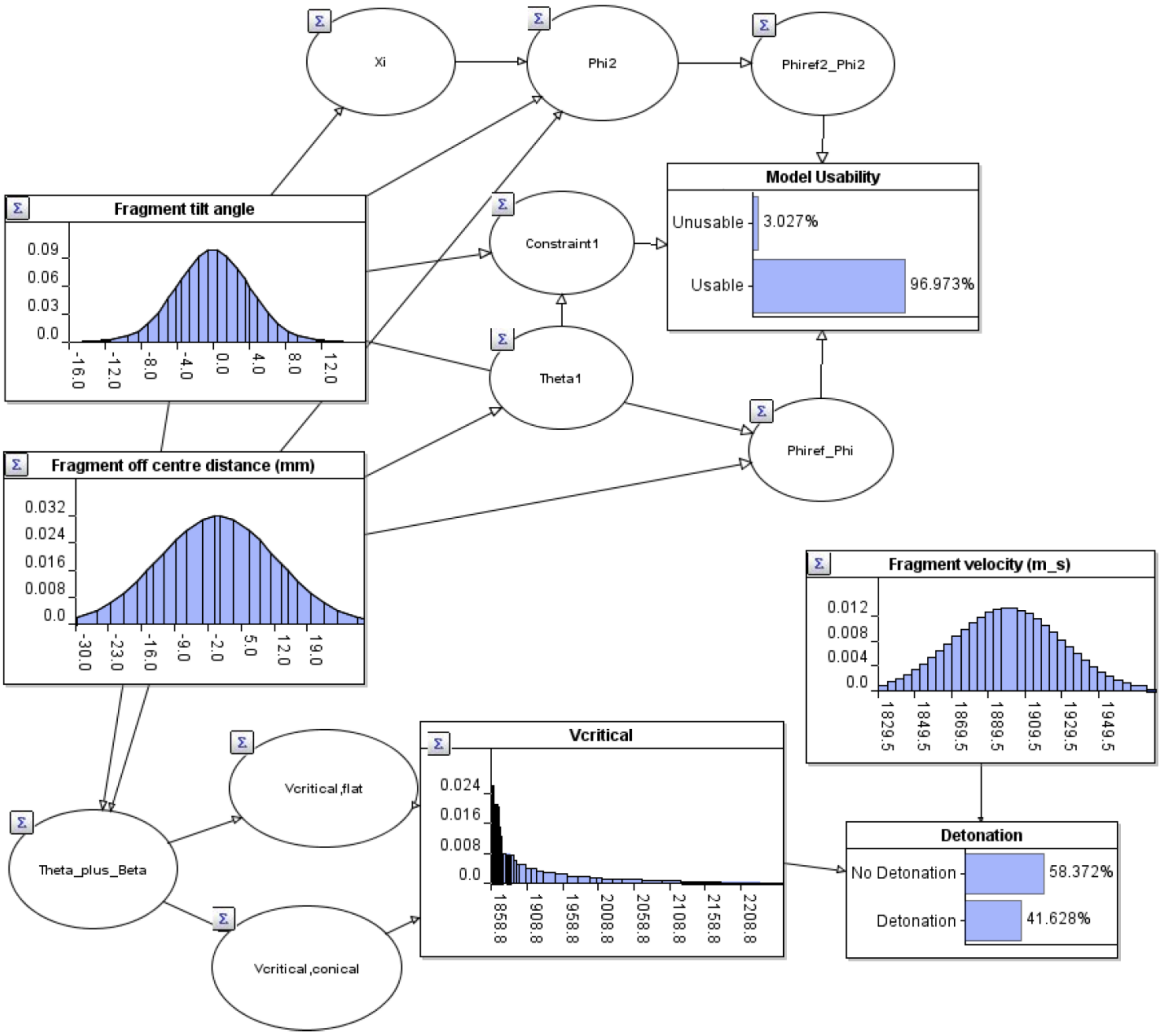


Figure 13. Example of a probabilistic initiation response model in the AgenaRisk BBN.

3 CASE STUDY

A case study was conducted for FI testing against a 155mm PBXN-9 filled warhead without a PIMS liner. Table 5 presents the JR Leibbrandt model parameters used for the study. With these parameters, the JR Leibbrandt model predicts deterministic $V_{Critical}$ of 1859 m/s. For the case study, the impact velocity, fragment tilt and impact offset were varied with Gaussian distributions that were chosen using engineering judgment based on experience. The mean impact velocity was chosen to be of 1830 m/s, mean fragment tilt was chosen to be zero and the mean impact offset was chosen to be zero. Table 6 presents the case study results: $\boldsymbol{\mu}$ is the mean value and $\boldsymbol{\sigma}$ is the one standard deviation value for the Gaussian distributions for each variable used in the case study. The results predict that an un-tilted fragment center impact with a 30 m/s standard deviation for the impact velocity variation will cause the warhead to detonate 16.6% of the time. When standard deviations of 4° for tilt and 12.5mm for impact point offset are assumed, the warhead is predicted to detonate 4.2% of the time. Further increasing the standard deviation of the impact point to 25mm and implementing a distribution cutoff of 35mm, the warhead is predicted to detonate 2.1% of the time.

The results indicate that if testing is conducted near critical values, significant number of passing tests are required in order to assure that a statistically meaningful passing result is achieved. Alternately, testing conditions would need to hold the most stressful test condition without significant variation to achieve confidence. In practice, such testing without significant variation is not achievable.

Table 5. JR Leibbrandt model parameters.

Warhead parameter	Symbol	Value	Fragment parameter	Symbol	Value
Warhead cover thickness	t	0.0086 m	Fragment critical dimension or diameter	d	0.0143 m
Cover plate protection coefficient	C	2.219	Projectile shape coefficient	B	0.270
Explosive sensitivity coefficient	A	87.56 $m^{3/2}/s$	Leibbrandt-coefficient	λ	3.832

Table 6. FI testing case study results.

V_0		β		X		Detonation [%]
μ	σ	μ	σ	μ	σ	
1830	0	0	0	0	0	0
1830	30	0	0	0	0	16.6
1830	30	0	4	0	2.5	8.9
1830	30	0	4	0	12.5	4.2
1830	30	0	4	0	25 [-35;35]	2.1

CONCLUSIONS

A probabilistic analytic model of initiation for the STANAG 4496 IM FI test was developed. The deterministic JR detonation initiation model was augmented to include impact point offset and fragment tilt against a curved munition case. The AgenaRisk BBN probability tool was subsequently used for variational impact conditions using the newly developed analytic explosive initiation model. A test case was run using the same 155mm diameter munition configuration that was used for the model calibration. The varied parameters included the fragment velocity, tilt and impact position offset. The results showed a large reduction in initiation probability can occur as a result of impact position offset and fragment tilt. These results indicate that if testing is conducted near critical values, significant number of passing tests are required in order to assure that a statistically meaningful passing result is achieved. It is possible that munitions “pass” fragment impact tests unjustly due to testing variation and a small number of tests. Alternately, testing conditions would need to hold the most stressful test condition without significant variation to achieve confidence. In practice, such testing without significant variation is not achievable. Perhaps observed tilt and off-center impact should be accounted for when reviewing test results.

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