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Technical Report

TR-05-2008
The Development of a Multi-hit Ballistics Test Procedure

November 2007

Prepared by

Bosik Technologies Limited
Ottawa, Ontario, Canada

For the
Canadian Police Research Centre
And
National Institute of Justice and Technical Support Working Group
Washington, D.C.

Acknowledgement

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Final Report

Extension to the Development of a Multi-hit Ballistics Test Procedure

Prepared for:

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Ottawa, Ontario

And

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November 30, 2007

Summary

This report describes the continued development of procedures for multi-hit testing of body armour at Bosik Technologies Limited (Bosik). The project was sponsored by the Canadian Police Research Centre (CPRC), and the Department of National Defence (DND) in Canada, and the National Institute of Justice (NIJ) in the U.S. The ultimate purpose of this project is to develop procedures that will be incorporated in the CGSB and NIJ test standards for multi-hit testing of body armour.

An initial phase on the development of a procedure for multi-hit testing of soft body armour was previously carried out in which it was shown that the use of the three barrelled gun developed at Bosik provides a precise dynamic simulation of the weapon utilized. Shot patterns of a number of actual automatic weapons were studied and documented for future reference. That phase of study also indicated that the dynamic effects from the tests can lead to significantly lower penetration of the body armour compared with traditionally test methods using static firing. Penetration velocities from multi-hit burst tests were found to be as much as 30% lower than those based on static tests. A number of additional tasks were identified as being necessary to be carried out to further define the test procedure. Hence, the current phase of the project was to carry out the seven sub-tasks identified in the following sections.

Brief descriptions of the tasks and their outputs are summarized in the following. The majority of the tests were carried out simulating the MP-5 automatic weapon utilizing 9 mm, 124 grain FMJ Round Nose bullets fired at 850 rounds per minute (RPM). Where other bullet types were used and when the rate of fire was varied, this was indicated. The shot pattern for these tests, as determined statistically for an MP-5 during Phase 1 of this project, was a triangular pattern with a spacing of 47mm, 7mm and 47mm between bullet locations. All tests were conducted at normal room temperature. Unless otherwise noted, all armour targets for this program consisted of Kevlar layers.

Task 1: Method of Attaching Armoured Vests:

During the initial three-shot bursts using the three barrel test fixture it was noted that unless the armour material is fixed to the test mannequin, the armour material could move significantly during the shot sequence leading to significant variability in the test results. Since shot spacing has been shown to be critical in the test results, the movement of the material between shots may result in more or less severe results than if carried out at the planned shot spacing. The objective of this task therefore was to limit the amount of movement of the armour between shots. The shot pattern for the tests is triangular, with spacing of 47 mm, 7mm and 47mm between the shots. This represents the 50 percentile, 5 percentile and 50 percentile spacing of shots from an MP-5 automatic weapon as determined statistically in the previous phase of this project. It was found during the testing that without strapping, the maximum average movement (from the ideal no movement) was 22.2 mm. This was reduced to a maximum of 9 mm with the use of 4 non-elastic straps. This was further reduced to a maximum of 7 mm with the use of 4 elastic straps. The use of 4 elastic straps (two vertical and two horizontal) is therefore recommended for the test procedure.
The elastic straps used were 48 inches long, 2 inches wide and .063 inches thick.
In practice it may not be practical to affix the body armour on a person such that it cannot move. However, a good fitting vest may limit the amount of movement and result in the protective levels realized during laboratory testing.

Task 2: Effects of Shot Sequence or Pattern Orientation

During the initial evaluations, it was noted in a preliminary way that certain shot sequences were more critical than others based on a triangular shot pattern. Also, some shot pattern orientations may be more critical than others. Based on the tests conducted, it was found that the most critical sequence (lowest penetration velocity) was found to be when firing the two closest positions (of a triangular shot pattern) sequentially first. Compared with other shot sequences, the V_{50} penetrations was lower by about 10%. When the firing pattern was rotated by 125 degrees, the results were found to vary by about 4% and this factor was not considered to be a significant factor for the materials tested. If a particular design is thought to be influenced by shot pattern, then a rotation of the pattern should be tested to ensure that this factor is either not significant, or determine to what extent it is significant.

Task 3: Angle Shots

The effects of angle of incident on the armour were carried out at angles of incidence of 90 degrees, 60 degrees and 30 degrees. These tests were carried out at firing rates of 850 RPM. The effect of angle on V_{50} was a maximum of 5 % compared with shots taken at an incident angle of 90 degrees. The actual V_{50} increased or decreased depending on the shot sequence used. Hence, although angle of incidence is important, it was not a major factor based on these tests.

Task 4: Effects of Firing Rates

This task determined the effect of firing rate on the V_{50} results, when varying firing rates from 850 RPM to 60 RPM. A lower penetration velocity was found to occur at higher firing rates. A 19% difference was determined in one case. Simulating the actual weapon firing rate is important in these tests.

Task 5: Different Body Armour Designs and Materials

Commercially supplied soft body armour samples were tested with single shot and multi-hit at incident angles of 90, 60 and 30 degrees to determine if any test anomalies were present. The armour layers in these were either Goldflex or Kevlar/Twaron. In all cases, the multi-hit procedure resulted in a lower V_{50} than for the single shot. This V_{50} was about 11% lower (for each type of material) at a 90 degree incident angle, and about 19% lower in one case at an incident angle of 60 degrees. The results were consistent with results previously obtained with Kevlar layers alone.

Task 6 Clay Equivalent Back Armour Measurement/Assessment for Multi-hit

The current multi-hit procedure does not include a method for scoring or assessing the back armour clay deformation. In a single shot procedure, the cavity in the clay backing is used to assess the level of trauma. In the current multi-hit methodology, a foam material is used as backing in order to provide support. Since the foam is resilient it does not provide a permanent record of the forces reacted by the backing like the clay would.

The purpose of this task was to determine an equivalent clay back output for multi-hit. A secondary goal was to determine that this equivalent methodology could be used in place of clay backing for single shot applications with an electronic scoring or assessment method. It is postulated that a more accurate measure of the total energy imparted by the projectile may be possible and will include the dynamic effects of the ballistic blunt trauma effects of single and multiple hits. The multiple impacts could be identified and diagnosed. The methodology carried out was as follows:

- Based on previous work conducted by Bosik, an instrumented segmented plate with computer based DAS was designed and constructed to measure the force–time distribution behind the armour during the impact.
- Using a “standard” armour and bullet speed, the first step was to determine the force distribution and deformation on clay backed blocks as a function of time. The assumption here was that the clay-backed cavity (depth and volume) could be characterized by a pressure time distribution with an instrumented backing plate.
- Utilizing a similar set up; the response (pressure distribution versus time) of the foam-backed system was determined with similar inputs. Correlations between the clay back and foam back were examined.
- The system was found to be adequately sensitive and the plots of the force distributions were found to be similar in shape to the cavity in the clay, but the correlation is non-linear.

- Samples of multi-hit testing have shown that the “trauma” consist of three impacts (for the three shot burst), spaced according to the firing rate of the weapon, and may therefore change the way that trauma is assessed in a human. For a single shot, there of course is only one impact which is currently assessed by the depth of indentation in the clay backing. As a first approximation, the trauma for a multi-hit on soft armour can be assessed a three single impacts, spaced at the firing rate of the weapon. The single impact trauma can be determined from the traditional method of clay backing.
- From the instrumented foam backed test results, it was noted that the first impact (of a three shot burst) was similar in shape and magnitude as a single shot (as would be expected). The subsequent following two shots are of lower magnitude than the first impact.
- The system when fully calibrated will have applications for single shot and multi-hit ballistics testing of body without the laborious manual task of working with clay backing.
- More correlating between the foam backed and clay backed results is required at this time. Different foam backing materials, with higher stiffness values, should be considered to determine that effect on the load cell output distributions. It would be beneficial to achieve load distributions that correlate more directly with the clay deformations for similar impacts. A larger instrumented plate, possibly with more sensors per unit area, should be developed to facilitate larger impact areas to be assessed. Ultimately, a self contained, fully automated system is required to meet the goals of, and replace clay backed systems.

Task 7: Multi-hit Testing of Hard Armour

Because of the brittle nature of hard armour in used in personal vests, it was of interest to determine in a preliminary way the effects of multi-hit testing compared with single shot testing. Personal body armour consisting of a ceramic plate and Kevlar backing was tested with 9mm, .45 ACP, 5.56mm and 7.62mm bullets, both single shot and multi-hit. In each case, there was significantly more damage to the hard armour during the multi-hit than the single shot. In some cases, at the maximum speed of the bullet, penetration of the hard armour occurred with the multi-hit but not with the single shot, for example the 9mm at 620 m/sec and .45 ACP at about 560 m/sec. In the case of the 7.62mm M80 148 grain bullet, the single shot complete penetration of the vest was at 936 m/sec, and only about 700 m/sec with the multi-hit. This is a reduction in V_{50} of about 25%. The multi-hit test procedure has a significant effect on the performance of hard body armour and should be examined in more detail.

In summary, the tasks were successfully completed based on the original intent and objectives. Procedures for testing soft body armour have now been established. It is recommended that more testing of variety of armour materials be evaluated, if possible, so that anomalies (if any), not uncovered in our studies, be identified and addressed. A preliminary method for assessing trauma from multi-hit testing has been identified. Additional studies are recommended to fully develop a “clay equivalent” instrumented trauma plate. Also, it was found that the multi-hit procedures have a significant effect on the V_{50} penetration results of hard armour. Specific procedures for multi-hi testing of hard armour should be developed, similar to the studies done for soft armour.

TABLE OF CONTENTS

List of Tables

List of Figures

1.0 Introduction

1.1 Background

For the last several years, Bosik Technologies Limited (Bosik) has been carrying out a program on the development of a multi-hit ballistics test procedure for the CPRC in Canada and the NIJ in the U.S. This was deemed necessary because current standards for conducting multi-hit testing of body armour do not incorporate repeat-ably the dynamic nature of machine guns.

This program was initiated as an unsolicited proposal from Bosik as a result of the development of a unique three barreled gun. This unique equipment simulates a three shot burst of fire from an automatic weapon, with accurate controls on firing rate and shot patterns. Because of these unique features, and the high repeatability of testing parameters, the equipment lends itself for use in the development of procedures for multi-hit ballistics testing of armour.

That project, entitled "Multi-hit Ballistics Test Procedure Development", was identified as Task Plan 738 of a joint United States and Canada agreement on cooperative research and development concerning counter terrorism. In the course of carrying out the initial phase of this work with the CPRC and the U.S. NIJ, significant results were obtained.
As compared to single shot ballistics testing (on which current multi-hit test standards are based), multi-hit is considerably more complex because of the dynamic nature of the bullet/vest interaction in multi-hit. Substantially different ballistics test results can be found between single shot and multi-hit testing because of these dynamic effects. In the previous studies, for the same bullet proof vest, penetration velocities for multi-hit tests were up to 30% lower than single shot tests. In reality, what this could mean is that a vest currently being worn that passed when tested with single shots of the same bullet type and velocity may actually fail if impacted by the same bullet type and velocity from a multi-hit weapon.

During the initial phase of studies, numbers of important follow on items were identified. A new agreement was achieved to carry out these follow on items in March, 2006. Since that time, work on the new phase of the project is progressing. This report has been prepared by Bosik and provides the status of the project effective January 31, 2007.

1.2 Objectives

The ultimate goal of this work is to develop laboratory procedures and equipment that can be used to repeatable and accurately assess the effects of bursts from automatic weapons on bullet proof vests. If successful, these procedures will lay the groundwork for national test standards in Canada (CGSB) and the U.S.A. (NIJ).

2.0 Work Statement

The following tasks were defined for this phase of work.

- Task 1 Method of Attaching Armoured Vests
- Task 2 Angle Shots
- Task 3 Effects of Shot Sequence or Pattern Orientation
- Task 4 Effects of Firing Rates
- Task 5 Different Body Armour Designs and Materials
- Task 6 Clay Equivalent Back Armour Measurement/Assessment for Multi-hit
- Task 7 Multi-hit Testing of Hard Armour

3.0 Methodology

The project was carried out in a series of tasks identified in the Work Statement at the Bosik ballistics laboratory in Ottawa. A review committee consisting of members from the CPRC/NRC, RCMP, DND and Bosik in Canada, and the NIJ and affiliates in the U.S.A. as well as Bosik provided guidance to the project. Periodic review meetings were held to review the progress and results and to provide input on subsequent activities. Additionally, some test samples (vests) were supplied through the committee members.

To conduct the tasks, the specialized equipment, knowledge and experience developed in the previous multi-hit studies were utilized. The primary tool that was previously developed at Bosik was the multi-barrelled universal receiver together with computer controls and software that was used to simulate the effects of machine gun fire. The three barrelled gun is shown in Figure 1 and the computer controls in Figure 2. This equipment was used to precisely simulate a particular automatic weapon shot burst with the added feature of precise targeting shot pattern. Calibrations to compensate for barrel to barrel variations in firing rates determined in the previous work were also applied during these tests to ensure precise results. The majority of the tests were carried out simulating the MP-5 automatic weapon utilizing Remington 9 mm, 124 grain FMJ round nose bullets fired at 850 RPM. Where other bullet types were used and when the rate of fire was varied, this was indicated. The shot pattern for these tests, as determined statistically for an MP-5 during phase 1 of this project, was a triangular pattern with a spacing of 47mm, 7mm and 47mm between bullet locations. All tests were conducted at normal room temperature. Unless otherwise noted, all armour targets for this program consisted of Kevlar layers.

Ammunition was individually hand loaded to ensure consistent, repeatable performance.

Figure 1: Three Barreled Gun for Simulating Machine Gun

Figure 2: Computer Controls for Setting Firing Rate and Measuring Speed

Speed measurement equipment was calibrated on a regular basis to ensure proper velocity results. Fixtures such as the mannequins previously developed were also used to study methods of attaching the vests, and for other similar tasks. In-house high speed video equipment (recording of up to 8000 fps) was utilized to study material movements between bullet impacts.

Also, it was determined previously; that the backing materials normally used in single shot testing (like plasticine) is not suitable for multi-hit testing. The first shot indents the clay not allowing for any support for the remaining two shots. Instead, materials must be used that adequately respond like human flesh so that the vest material is supported between each shot. Our studies carried out on a variety of backing materials determined that a foam backing can adequately provide the support and response for the tests. The foam backing is therefore used. It consisted of Minicel L-200 white 2" thick, 1.5 - 2.5 lb/ft3, Tensile Strength 28-50 psi.

The target was arranged as shown in Figures 3 to 5. A mannequin (Goldorac II) was first layered with the Minicel foam as shown in Figure 3 to provide the necessary backing material. The test bullet proof vest was then placed over the foam.

Figure 3: Foam Placed On Mannequin

The vest containing 22 layers of Kevlar was then placed over the foam as shown in Figures 4 and 5 below.

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Figure 4: Mannequin with Vest and Foam Inserted

Figure 5: Complete Target Vest over Foam and Mannequin

4.0 Results

The activities carried out in each task are described in the following section.

Task 1: Method of Attachment for Armour Vests

During three shot bursts using the three barrel test fixture it was noted that unless the armour material is fixed to the test mannequin, the armour material could move significantly during the shot sequence leading to significant variability in the test results. Since shot spacing has previously been shown to be critical in the test results, the movement of the material between shots may result in more or less severe results than if carried out at the planned shot spacing. The objective of this task therefore was to limit the amount of movement of the armour between shots. The shot pattern for the tests was triangular, with spacing of 47 mm, 7mm and 47mm between the shots as shown in Figure 6. This represents the 50 percentile, 5 percentile and 50 percentile spacing, respectively, of shots from an MP-5 automatic weapon as determined (by the Royal Military College in Kingston, Ontario) statistically in the previous phase of this project. All tests were conducted at 850 RPM and 0 angles of incidence.

To evaluate the effectiveness of the vest restraint method, two series of three-shot burst tests were conducted to compare the difference of shot spacing with and without strapping of the armour (Kevlar vest) to the test mannequin. The results of the two series are given in Tables 1 and 2, respectively. The ideal spacing (without movement) between shots is of course 47mm, 7mm, and 47 mm (as seen in Figure 6).

In the first series of tests, the armour was mounted on the mannequin and either used no straps or four non-elastic straps. It was found in this series of testing that without strapping, the maximum average movement from the ideal (no movement) was 25.5 mm. This was reduced to a maximum of 10.5 mm with the use of 4 non-elastic straps.

In the second series, it is seen that the average increase in distance between the shots on one of the long sides was 18.25 mm without straps, 9.75 with non- elastic straps, and 5.5 mm with elastic straps. For the other long (47 mm) side, the average increase in distance between the shots was 22.25 mm without straps, 8.25 with non- elastic straps, and 8.75 mm with elastic straps. For the third side with the shortest distance between the shots, the average increase in distance between the shots was 8 mm without straps, 5.5 mm with non- elastic straps, and 6.5 mm with elastic straps.

Based on these results, it is concluded that the maximum movement between shots from the elastic straps are more or less equal to or better than non- elastic straps and should therefore be used during the tests.

The elastic straps used were 48 “long, 2 inches wide and .063 inches thick.
In practice it may not be practical to affix the body armour on a person such that it will not move between shots. However, a good fitting vest will limit the amount of movement and should result in the protective levels realized during laboratory testing. Figure 7 below illustrates the attachment method.

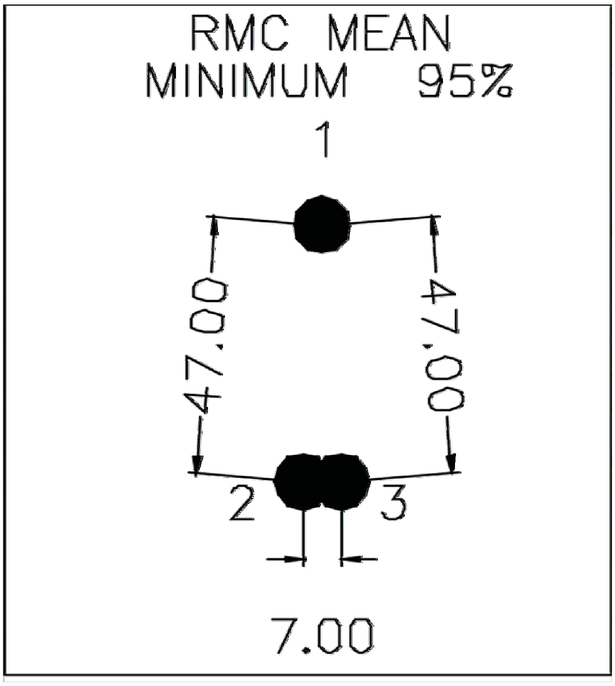


Figure 6: Triangular Shot Pattern Used In the Testing

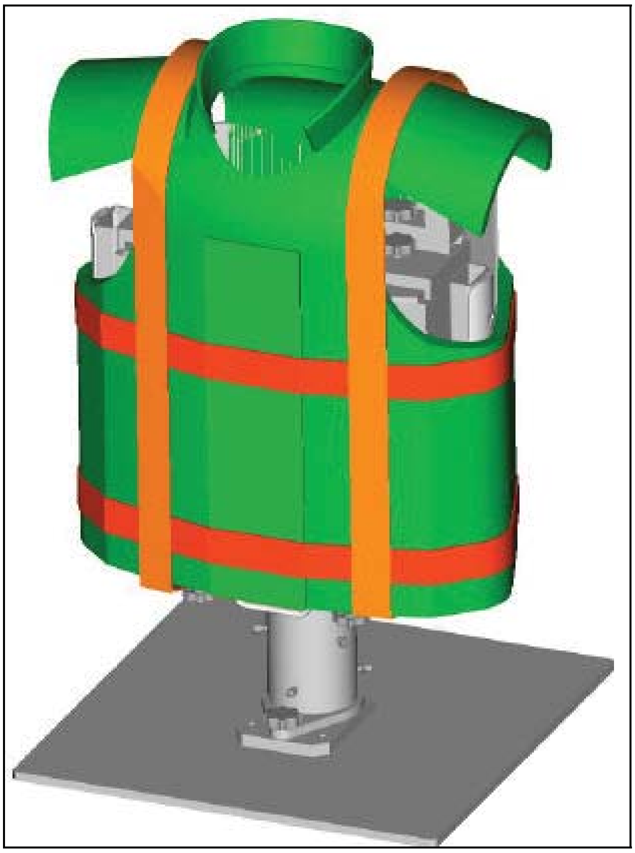


Figure 7: Straps Used During Testing of Vests

Table 1: Series 1- Shot Spacing Comparison, Non-elastic Strapped and Non Strapped Burst Tests

Firing Rate: 850 (RPM)	**Distance Between Bullet Impact Points**			
Type of Strapping	**Shot No.**	**Distance Between 1 & 2 [mm]**	**Distance Between 2 & 3 [mm]**	**Distance Between 3 & 1 [mm]**
No Straps	**Burst 1**	68	20	69
	Ideal Spacing	47 (50%)	7(5%)	47(50%)
	Increase From Ideal Spacing	**21**	**14**	**22**
	Burst 2	75	23	76
	Ideal Spacing	47 (50%)	7(5%)	47(50%)
	Increase From Ideal Spacing	**28**	**16**	**29**
	Average increase	**25**	**15**	**25.5**
With Non-elastic Straps	**Burst 1**	55	26	55
	Ideal Spacing	47 (50%)	7(5%)	47(50%)
	Increase From Ideal Spacing	**8**	**19**	**8**
	Burst 2	60	20	59
	Ideal Spacing	47 (50%)	7(5%)	47(50%)
	Increase From Ideal Spacing	**13**	**13**	**12**
	Average increase	**10.5**	**16**	**10**

Table 2: Series 2- Shot Spacing Comparison, Non Strapped, Non-elastic Strapped and Elastic Strapped Burst Tests

	Burst	Shot 1-2 (mm)	Shot 2-3 (mm)	Shot 3-1 (mm)
With No Straps	1	53	18	59
	2	71	16	65
	3	75	10	74
	4	62	16	79
	Average	65.25	15	69.25
	Average increase from ideal (mm)	**18.25**	**8**	**22.25**
With Non-elastic Straps	**Burst**			
	1	53	12	50
	2	51	10	52
	3	59	13	58
	4	64	15	61
	Average	56.75	12.5	55.25
	Average increase from ideal (mm)	**9.75**	**5.5**	**8.25**
With Elastic Straps	**Burst**	55	26	55
	1	53	17	54
	2	53	13	53
	3	51	13	53
	4	53	11	55
	Average	52.5	13.5	53.75
	Average increase from ideal (mm)	**5.5**	**6.5**	**8.75**

Task 2: Effect of Angle of Incidence on V-50

The effects of angle of incident on the armour were carried out at angles of incidence of 90 degrees, 60 degrees and 30 degrees. These tests were carried out at firing rates of 850 RPM and 60 RPM, and at shot sequences of 1,2,3; 2,1,3; and 2,3,1. The summary of the results are given in Table 3 below. The variability in the results is summarized in Table 4. As seen in Table 4, the effect of angle of incidence on V-50 was a maximum of 5 % compared with shots taken at an incident angle of 90 degrees. The actual V-50 increased or decreased depending on the shot sequence used. Hence although angle of incidence is important, it was not a major factor based on these tests.

Table 3: Summary of V50 Results versus Angle, Firing Rate and Shot Sequence

Summary of V_{50}					
Shot Sequence		**Shot Angle**			
2, 1, 3		90^o	60^o	30^o	
Rate of Fire	850	478	457	452	
	60	502	493	484	
Shot Sequence		**Shot Angle**			**125^o**
2, 3, 1		90^o	60^o	30^o	Rotation
Rate of Fire	850	424	435	423	445
	60	445	441	502	
Shot Sequence		**Shot Angle**			
1, 2, 3		90^o	60^o	30^o	
Rate of Fire	850	449	449	469	
	60	480	465	492	

Table 4: Variability of V-50 versus Angle of incidence

Variability (%)			
Shot Sequence	Angle of Incidence		
	90	60	30
2,1,3	0	4	5
2,3,1	0	-3	4
1,2,3	0	0	-4

Task 3: Effect of Shot Sequence or Pattern Orientation

During the initial evaluations, it was noted in a preliminary way that certain shot sequences were more critical than others. This further confirms the importance of dynamic testing. Also, some shot pattern orientations may be more critical than others. Hence this task was carried out to explore those factors by determining the burst V-50 values under a different set of conditions.

In each case the standard shot pattern (triangular pattern having dimensions of 47mm, 7mm and 47mm, as per Figure 6) was conducted at a firing rate of 850 RPM. The results are shown in Table 3. The variability in results is analyzed in Table 5. Based on the tests conducted, it was found that the most critical sequence (lowest penetration velocity) was found to be when firing the two closest positions first: firing sequence 2-3-1 in Figure 6 above. The difference in the V-50 penetration velocity between firing sequence 1-2-3 and 2-3-1 was about 10%. Hence sequence 2-3-1 should be used in the procedure to provide the most conservative results. Shot sequence 2-3-1 was rotated 125 degrees counter clock wise and tested at 850 RPM. The result showed that the V_{50} was higher compared to the non-rotated position by about 4 %. For the tests conducted, this was not thought to be a significant factor although it may be significant for some vest designs. However, rotation of the shot sequence should be used if a specific design, and the materials pattern, could possibly be affected by the rotation of the shot pattern.

Table 5: Variability in V-50 from Shot Sequence at Firing Rate of 850 RPM

Shot Sequence	Angle (degree)	Angle (degree)	Angle (degree)
	90	**60**	**30**
	Variability (%)	**Variability (%)**	**Variability (%)**
2,1,3	6	2	-4
2,3,1	-6	-3	-10
1,2,3	0	0	0

Task 4: Effects of Firing Rates

In one of the traditional methods of evaluating body armour against automatic weapons firing, the procedure was to shoot three separate shots on the armour at a prescribed circular pattern. This method ignored the firing rate of the weapon and essentially evaluated the body armour statically. Therefore, any dynamic influences from the interaction of firing rate on the response of the body armour were not considered in this static test method.

This task was carried out to determine how firing rates may have an affect on the V_{50} results. During the first part of this task, results were obtained at a nominal firing rate of 850 RPM. Then the results were obtained at a low rate of fire (60 RPM) while conducting tests at angle of incidents of 90, 60 and 30 degrees, and with variation in firing sequence. All tests were conducted on Kevlar vests. The results are given in Table 6 with additional analyses given in Table 7. The average V_{50} at 60 RPM was higher than at 850 RPM in all cases. In the largest differential, the “virtually” static V_{50} (at 60 RPM) was 19% higher than the dynamic V_{50} at 850 RPM.

It is of interest to note that this was for the worst case (lowest V_{50}) dynamically, at a 30 angle of incidence. It also points to the fact that there can be a significant error in the V_{50} if it is determined statically (three shots at a very low firing rate). The static V_{50} test results, by virtue of the fact that they are higher than real (dynamic) results, provide a false sense of safety. These results show that the test should incorporate the dynamic aspects of the firing rate and shot pattern of the actual weapon.

Table 6: Effects of Firing Rate on V-50

Shot Sequence		**Shot Angle**		
2, 1, 3		90°	60°	30°
Rate of Fire	850	478	457	452
	60	502	493	484

Shot Sequence		**Shot Angle**			125°
2, 3, 1		90°	60°	30°	Rotation
Rate of Fire	850	424	435	423	445
	60	445	441	502	

Shot Sequence		**Shot Angle**		
1, 2, 3		90°	60°	30°
Rate of Fire	850	449	449	469
	60	480	465	492

Table 7: Percent Increase in V-50 at 60 RPM from 850 RPM

Shot Sequence	Angle 90 Deg.	Angle 60 Deg.	Angle 30 Deg.
2,1,3	5 %	8%	7%
2,3,1	5%	1%	19%
1,2,3	7%	4%	5%

Task 5: Different Body Armour Designs and Materials

Commercially supplied soft body armour samples were tested with single shot and multi-hit at incident angles of 0, 30 and 60 degrees. The armour layers in these were either Goldflex or Kevlar/Twaron. The results are shown in Tables 8 and 9. In all cases, the multi-hit procedure resulted in a lower V_{50} than for the single shot. This V_{50} was about 11 % lower (for each type of material) at a 0 degree incident angle, and about 19% lower in one case at an incident angle of 60 degrees. The results for the commercially available body armour samples tested in this task produced similar results to the Kevlar samples previously tested in this program. The procedures utilized did not demonstrate any inconsistencies.

Figure 8: View of Commercially Available Soft Armour Sample

Table 8: Single Shot Test Results on Commercially Available Body Armour

Sample Description	Angle of Incidence (degrees)	Single Shot V_{50} (m/s)
Female back 24 layers Goldflex	0	586
Female front 24 layers Goldflex	0	580
Male front 24 layers Kevlar/Twaron	0	511
Male back 24 layers Kevlar/Twaron	0	528

Table 9: Comparison of Single Shot and Multi-hit Test Results of Commercially Available Body Armour

Sample Description	Angle of Incidence (degrees)	Single shot V50 (m/sec.)	Multi-hit 850 RPM V50 (m/sec.)	Change (m/sec.)	Change (%)
Female 24 layers Goldflex	0	583 (average)	519	64	11
	30		507	76	13
	60		542	41	7
Male 24 layers Kevlar/Twaron	0	520 (average)	463	57	11
	30		466	54	10
	60		419	101	19

Task 6: Clay Equivalent Back Armour Measurement/Assessment for Multi-hit

The current multi-hit procedure does not include a method for scoring or assessing the back armour clay deformation. In a single shot procedure, the cavity in the clay backing is used to assess the level of trauma. In the current multi-hit methodology, a foam material is used as backing in order to provide support. Since the foam is resilient it does not provide a permanent record of the forces reacted by the backing like the clay would.

The purpose of this task was to determine an equivalent clay back output for multi-hit. A secondary goal was to determine that this equivalent methodology could be used in place of clay backing for single shot applications with an electronic scoring or assessment method. It is postulated that a more accurate measure of the total energy imparted by the projectile may be possible and will include the dynamic effects of the ballistic blunt trauma effects of single and multiple hits. The multiple impacts could be identified and diagnosed. The methodology carried out was as follows:

Set Up:

Based on previous work conducted by Bosik, an instrumented segmented plate with computer based DAS was designed and constructed to measure the force–time distribution behind the armour during the impact. This system is shown in Figures 9, 10 and 11. The complete assembly of the clay equivalent test system consists of the following as seen from the weapon side:

- target test material (vest test material)
- foam backing material
- rubber diaphragm
- loading plates: array of 16 plates each 1.5 inch square forming a 6” x 6” target
- guide plates for supporting load cell rods
- load cell rods for transmitting force from loading plate to load cell
- load cells (total 16 , one for each loading plate)
- highly rigid support plate/frame

The load cells were strain gauged type connected to computer based National Instrument software Data Acquisition System. During a shot, data from all 16 load cells were obtained as a function of time. The data was then converted to excel files.
The excel files were then further analyzed by converting the information to excel plots for two-dimensional views, or “DPLOTS”, which provides an isometric (three dimensional) view.

Figure 9: Clay Equivalent Test Fixture (Photo)

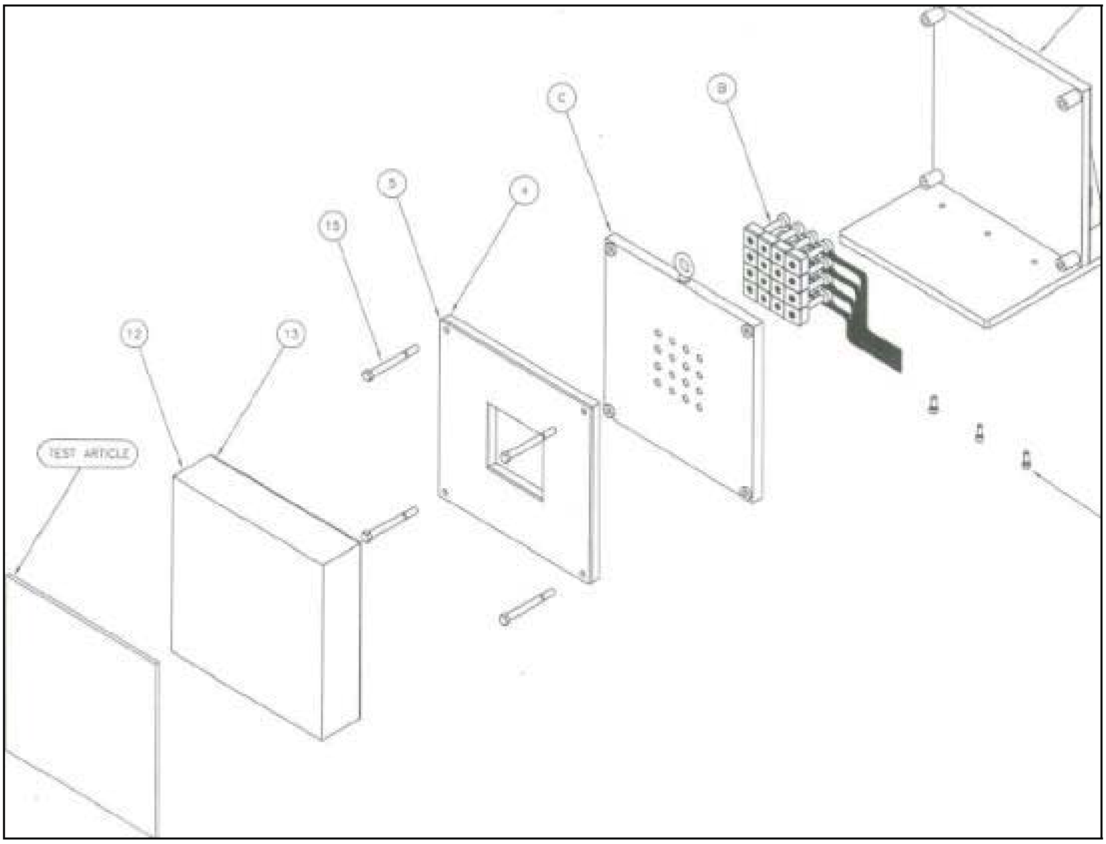


Figure 10: Blow Up Drawing Showing Components of Clay Equivalent Fixture

LC1	**LC2**	**LC3**	**LC4**
LC5	**LC6**	**LC7**	**LC8**
LC9	**LC10**	**LC11**	**LC12**
LC13	**LC14**	**LC15**	**LC16**

Figure 11: Front View of Instrumented Plate with 16 Load Cells and the Designation of the Load Cells

Single Shot Trauma Determination Comparisons:

The first step in the determination of the trauma comparisons with the clay back system and the instrumented plate system was to determine the levels of trauma for “standard” tests with clay backing. To conduct these tests, the normal soft armour shoot pack was mounted and tested with the 9 mm single shot at levels of 100% and 75% of the previously determined multi-hit V_{50} penetration velocities. The set up with clay backing is shown in Figure 12. This consisted of the test sample armour, backed by a frame supporting the clay backing material. Sample clay back with cavity following impact is shown in Figure 13. Examples of the measured cavity based on a centimeter square grid are shown in Figures 14 ands 15, for tests conducted at 100% velocity and 75% velocity. The maximum indentations for these examples were 31 mm and 22 mm, respectively. Table 10 shows a summary of the indentations for a number of impacts. As seen in Table 10, test to test repeatability for peak indentation was good with the maximum variability being about 5% of the average.

Sample three dimensional isometric plots (Dplots) of indentation versus distance along the plane of the clay are given in Figures 16 and 18 for the data given in Figures 14 and 15, respectively. The force distribution, measured during a 100% (448 m/s) impact on clay backing is plotted in Figure 17. It is seen, that the plots of indentation versus distance along the clay (Figures 14 and 15) yields to hemispheric shapes. A plot of the load distribution (Figure 17) has a similar shape, but perhaps not as symmetric as the actual indentations of Figures 16 and 18. This implies a non-linear relationship between the clay deformation and impact load.

Table 10: Summary of Clay Indentations (Trauma) for 9mm Impacts

Shot Number	**Speed (m/s)**	**Maximum Indentation (mm)**	**Nominal Single Shot V-50 (%)**
1	466	31	100
2	468	28	100
3	461	28	100
Average	**456**	**29**	
1	344	22	75
2	351	22	75
3	343	21	75
4	348	22	75
Average	**347**	**21.8**	

Isometric views (DPLOTS) for the same data are given in Figures 16 and 17. The isometric views allow for easy visualization of the data and DPLOT also allows for determination of the volumes of the cavities.

Figure 12: Set Up For Determining V-50 Penetration Velocities with Clay Backing

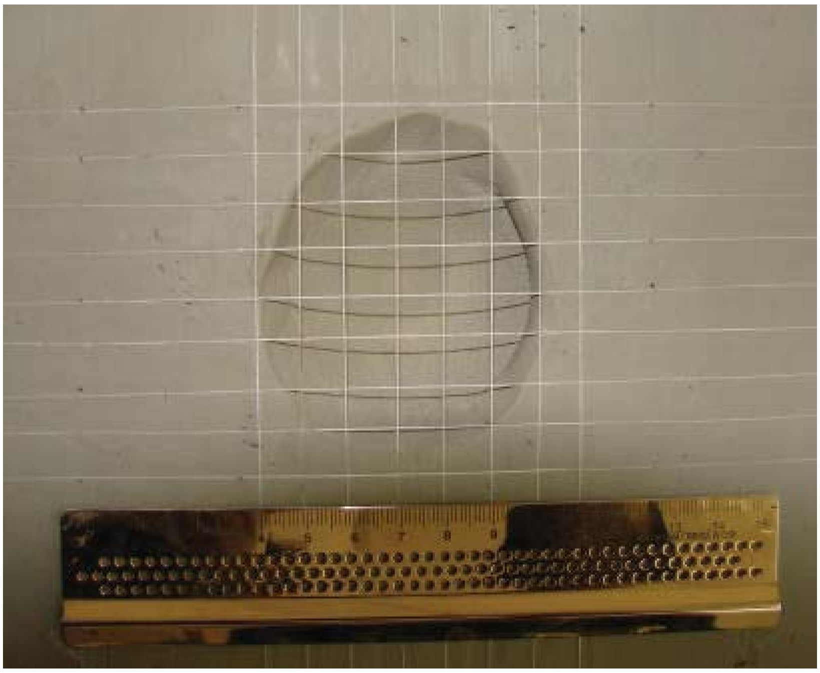
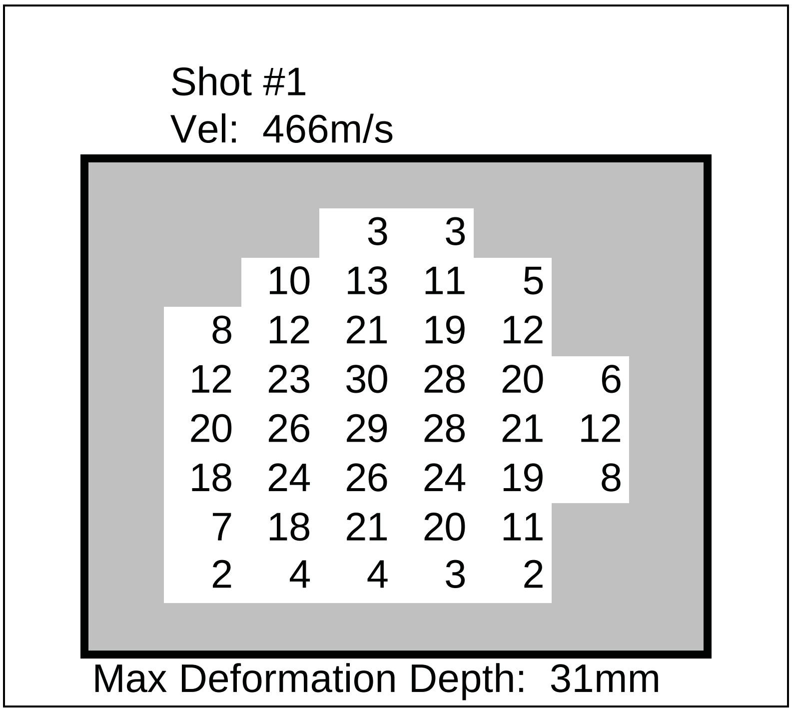


Figure 13: Cavity in Clay Depicting Trauma Level

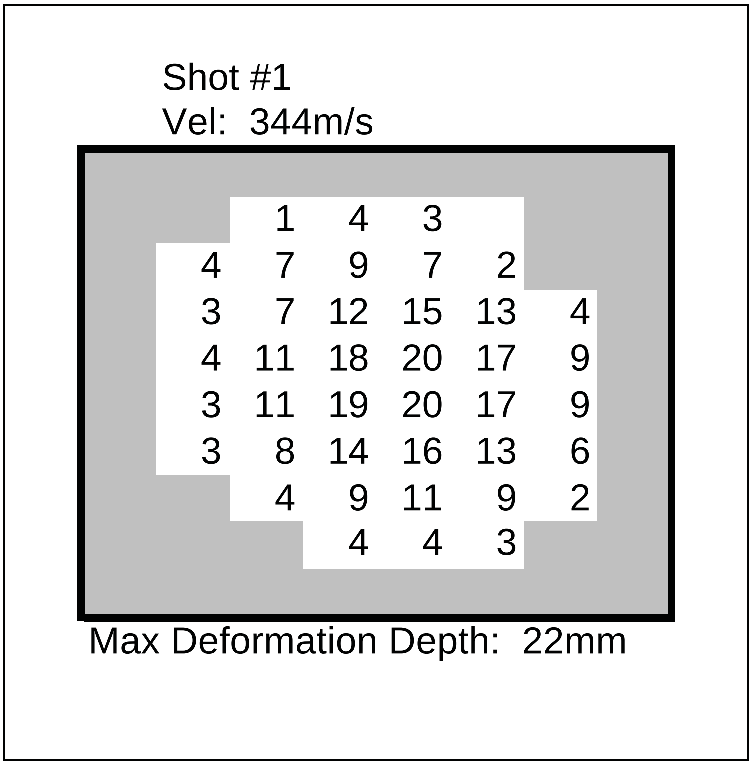


Shot #1
Vel: 466m/s

		3	3		
	10	13	11	5	
8	12	21	19	12	
12	23	30	28	20	6
20	26	29	28	21	12
18	24	26	24	19	8
7	18	21	20	11	
2	4	4	3	2	

Max Deformation Depth: 31mm

Figure 14: Cavity Indentation Distribution for 9mm Impact at 466 m/s



Shot #1
Vel: 344m/s

	1	4	3		
4	7	9	7	2	
3	7	12	15	13	4
4	11	18	20	17	9
3	11	19	20	17	9
3	8	14	16	13	6
	4	9	11	9	2
		4	4	3	

Max Deformation Depth: 22mm

Figure 15: Cavity Indentation Distribution for 9mm Impact at 344 m/s

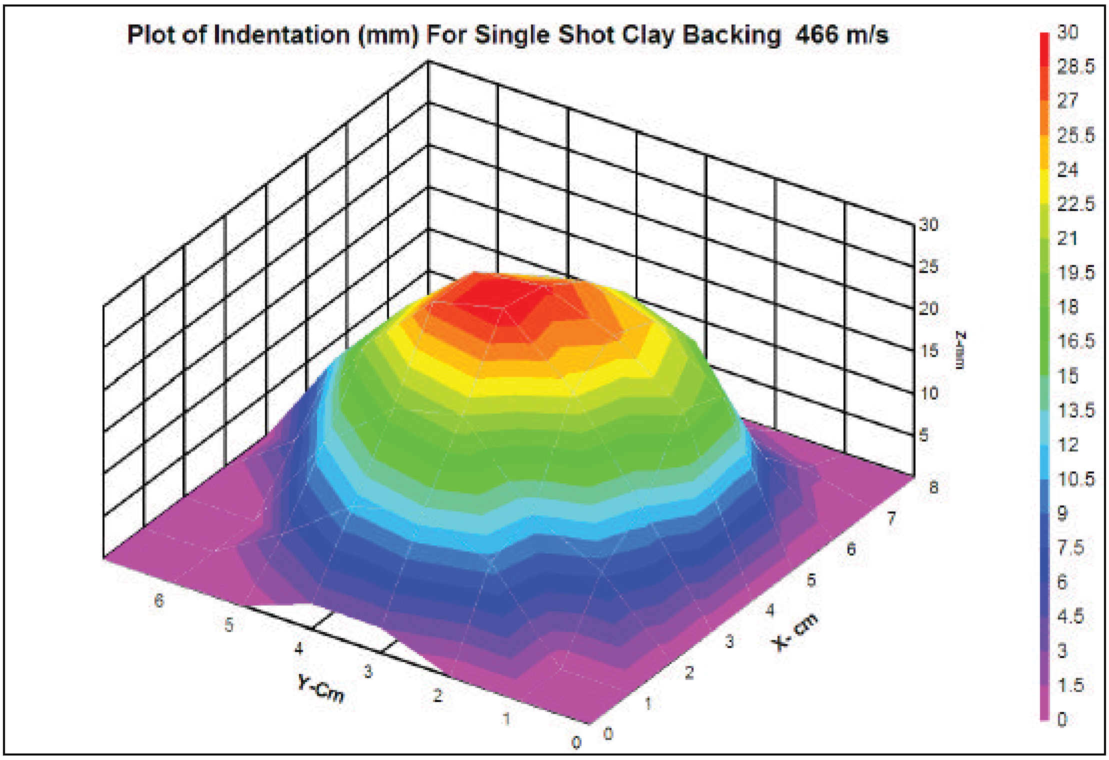


Figure 16: Plot of Measured Indentation Distribution (Cavity) Clay Single Shot at 466 m/s

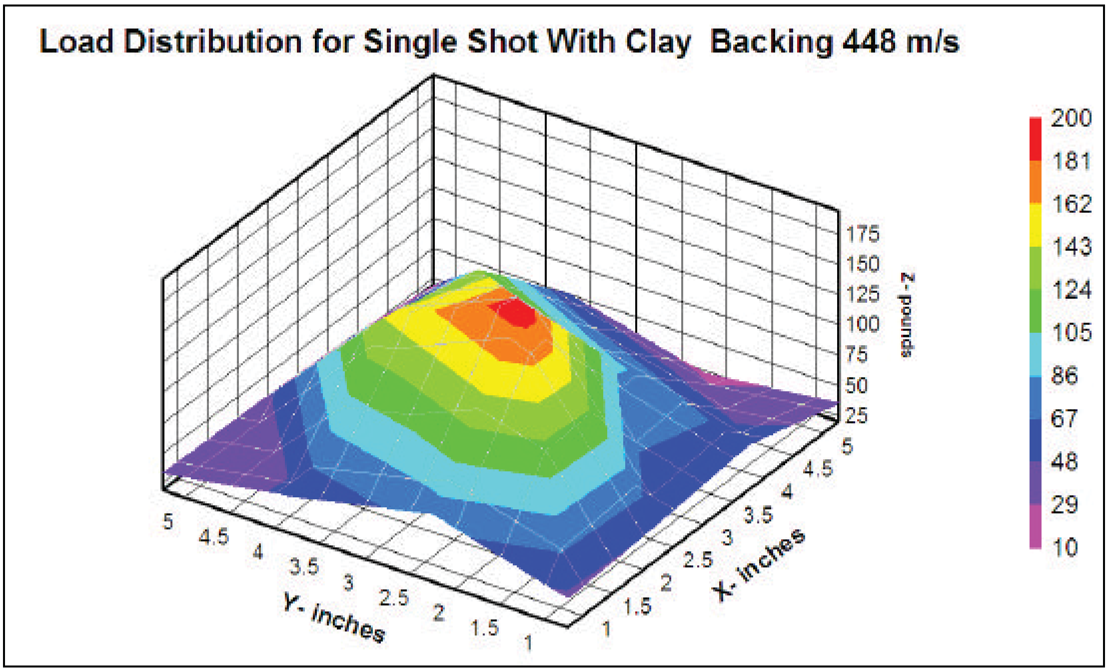


Figure 17: Load Distribution for Single Shot with Clay Backing at 448 m/s

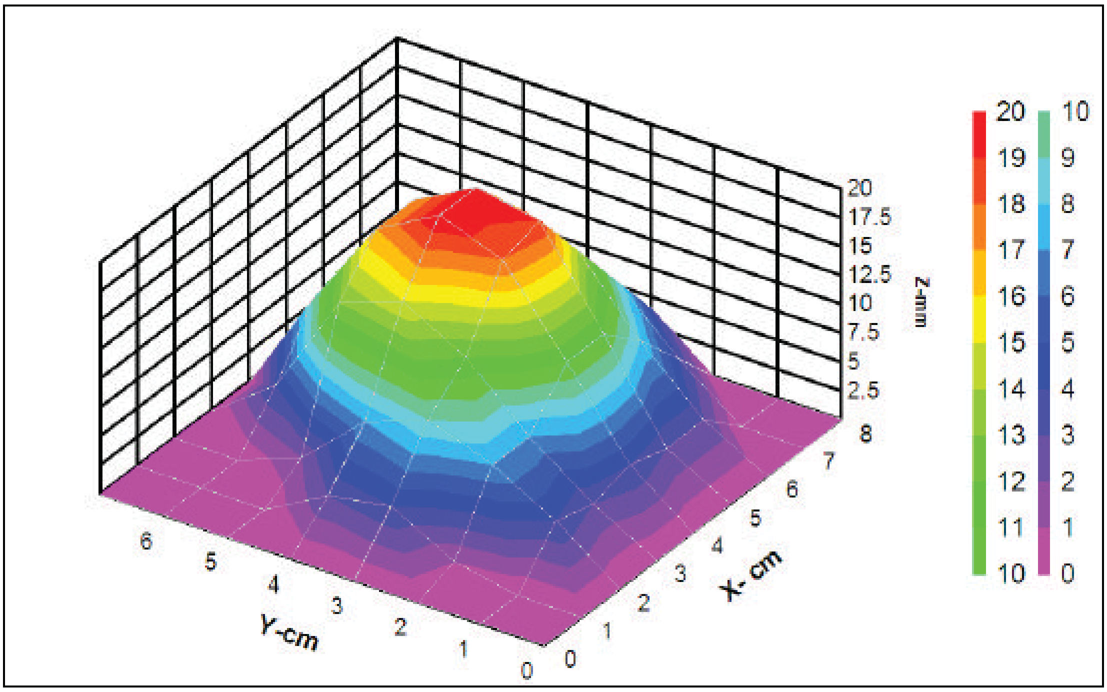


Figure 18: Plot of Measured Indentation Distribution (Cavity) Clay, Single Shot at 344 m/s

The next step in the evaluation of single shot correlations between clay and foam backing test samples was to obtain the force distributions from foam backed samples. The load cell outputs of the instrumented plate for a foam backed impact at 340 m/s are shown in Figure 19. The peak load of the highest reading load cell was about 240 pounds. An isometric plot of the peak loads from the load cell outputs from Figure 19 is given in Figure 20. A similar isometric plot for a single shot carried out on clay backing at a speed of 449 m/s is shown in Figure 21. From the load distributions given in Figures 20 and 21, it is first seen that the load cell outputs were suitable sensitive and the loads were well within the range of the instrumentation. Also seen is the isometric shapes from the load cell plots are more conical than the hemispherical plots of the clay indentations of Figures 16 and 18, shown previously.

This further implies a non-linear relationship between bullet load and deformation of the clay. Also, when comparing the peak loads from impacts carried out at 340 m/s (Figure 19) and impact carried out at 449 m/s (Figure 21), the peak load at 449 m/s was about 1100 pounds, and the peak load at 340 m/s was about 240 pounds, less than ¼ the value. When comparing the maximum clay indentations for the two shots, at 449 m/s the maximum indentation was 31 mm, and at 340 m/s the maximum indentation was 22 mm. At the 340 m/s, the indentation was about 70 % of the indentation at 449 m/s. Again, this indicates a very non-linear relationship between load (as transmitted through the foam) and deformation in the clay. Part of this effect is likely the characteristics of the backing material used. For example, if the stiffness of the foam was increased, this would likely “spread out” the load from the bullet, and the load outputs distributions would be flatter- more like the shape for clay.

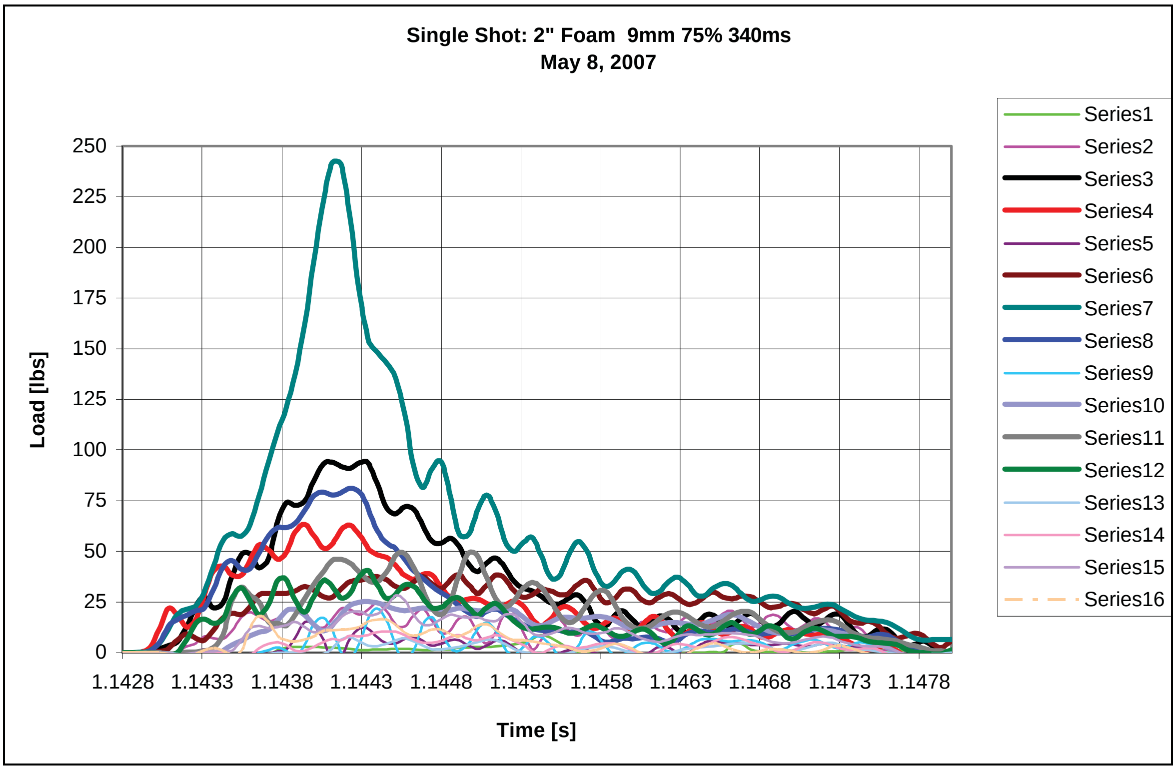


Figure 19: Load Cell Response as a Function of Time, Single Shot Foam Backing at 340 m/s

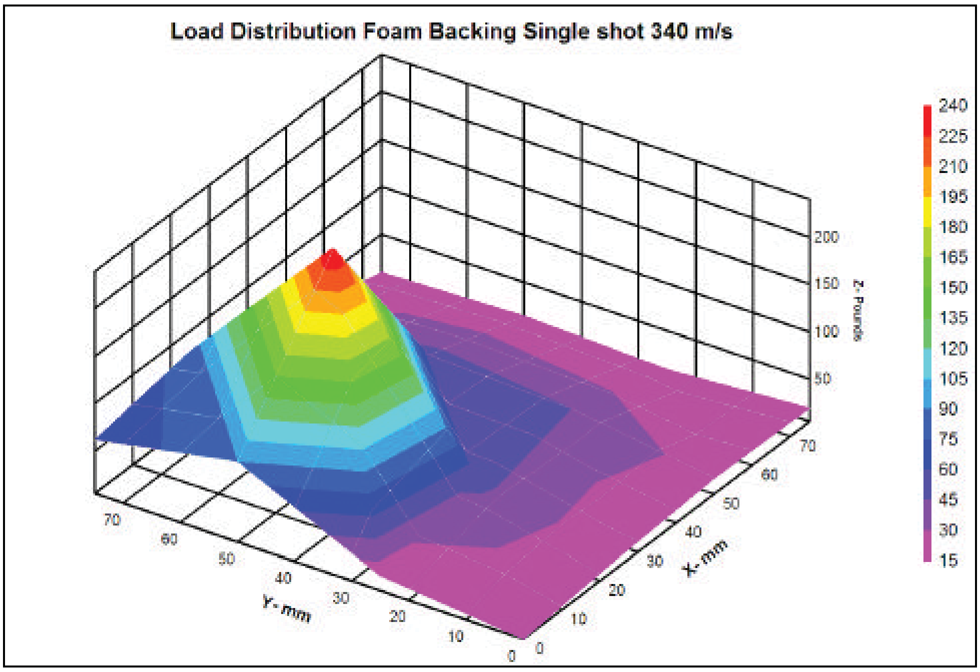


Figure 20: Isometric Plot of Peak Load Distribution, Single Shot with Foam Backing at 340 m/s

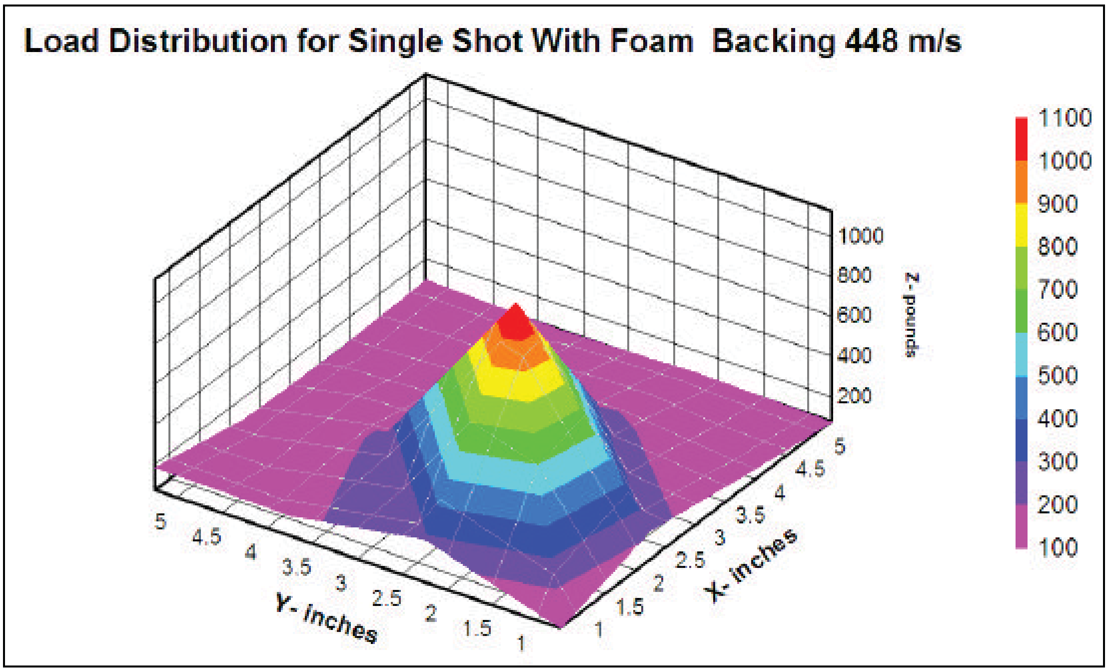


Figure 21: Load Distribution for Single Shot with Foam Backing at 449 m/s

Multi-hit Test Correlation:

The load cell outputs of a three shot multi-hit burst sample, tested at a nominal speed of 340 m/s, is shown in Figure 22. As can be seen, each shot of the burst occurred at about 70 milliseconds spacing, which correlates with the firing rate of about 850 rounds per minute. Also what is seen, is that the maximum load seen in the first bullet striking the target is greater (about 240 pounds) than the loads from each bullet (about 55 pounds) of the subsequent impacts. The rational for this difference is not known at this stage but it does raise some interesting issues pertaining to the trauma from multi-hit strikes. The individual load cell outputs of each of shots 1, 2 and 3 of the multi-hit burst are enlarged given in Figures 23, 25 and 27. The peak loads of the corresponding information are plotted in Figures 24, 26 and 28.

First it is noted that the load distribution for the first shot of the multi-hit shot (as shown in Figure 23) is very similar to the single shot load distribution as shown in Figure 19, carried out at the same impact speed of 340 m/s. This was to be expected and confirms the shot to shot repeatability of the system. As a first approximation also, the trauma from a multi-hit can be taken as three impacts, each of them acting for about 6 milliseconds, (Figure 29) with a maximum severity of a single impact, but delivered at the firing rate of the weapon. Why the maximum loads of the subsequent impacts from a multi-hit burst were lower than the first impact may be attributed, at least in part, to the way the actual loading takes place. In a multi-hit impact, the first impact would in part remove the slack in the armouring materials around the impact, and the subsequent impacts occur on the tightened materials. The resistance offered by the tightened materials for the last two shots would possibly reduce the resistive loads measured by the load cells. These aspects require more detailed research.

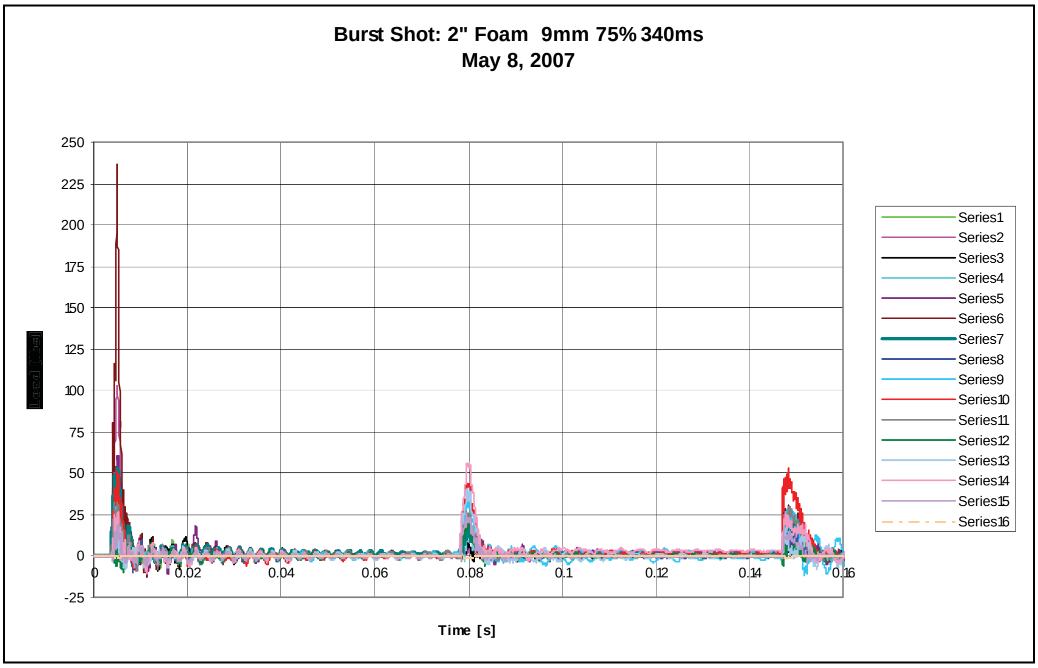


Figure 22: Load Cell Output as a Function of Time from Foam Backed Target Three Shot Burst Fired at 340 m/s

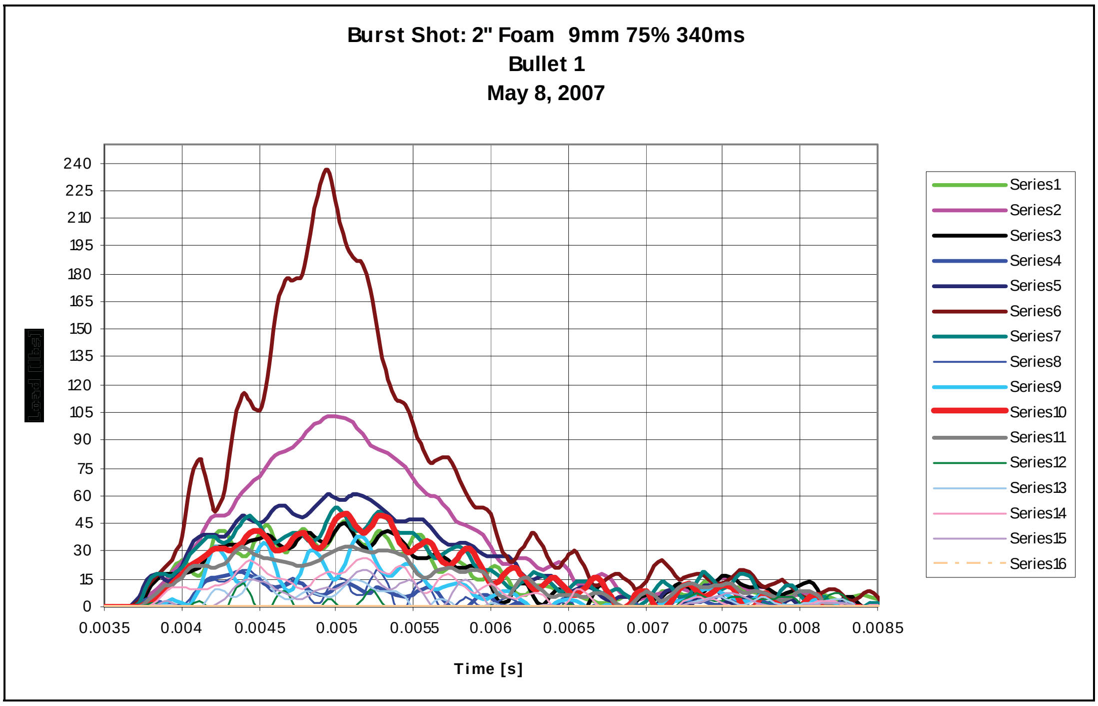


Figure 23: Load Cell Outputs for Bullet 1 for Multi-Hit Test in Figure 22

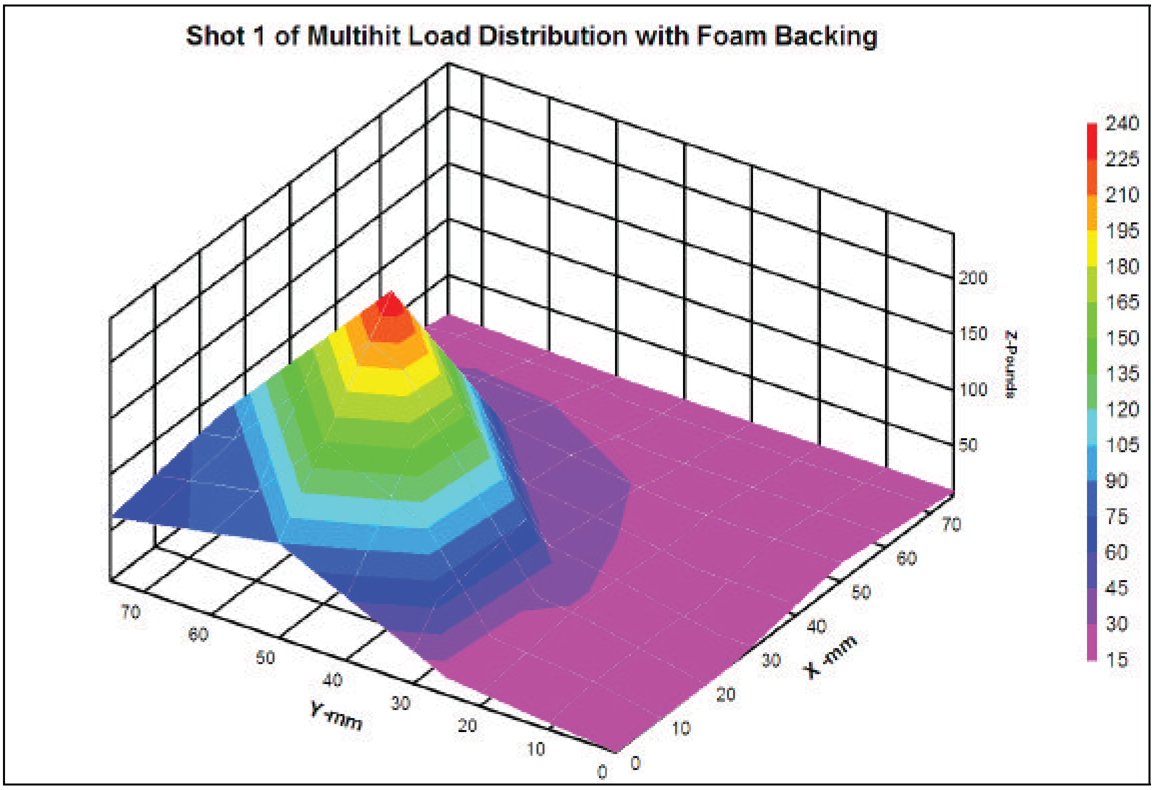


Figure 24: Peak Load Distribution of Foam Backing, Bullet 1 in Figure 22 at 340 m/s

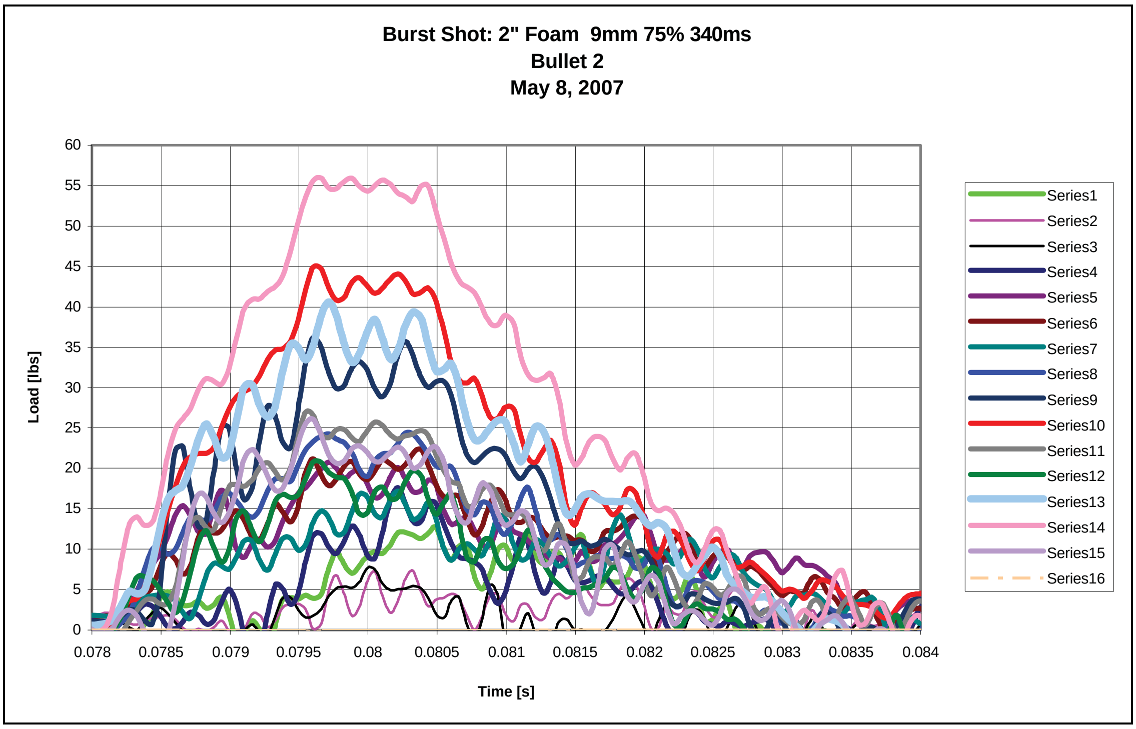


Figure 25: Load Cell Outputs for Bullet 2 for Multi-Hit Test in Figure 22

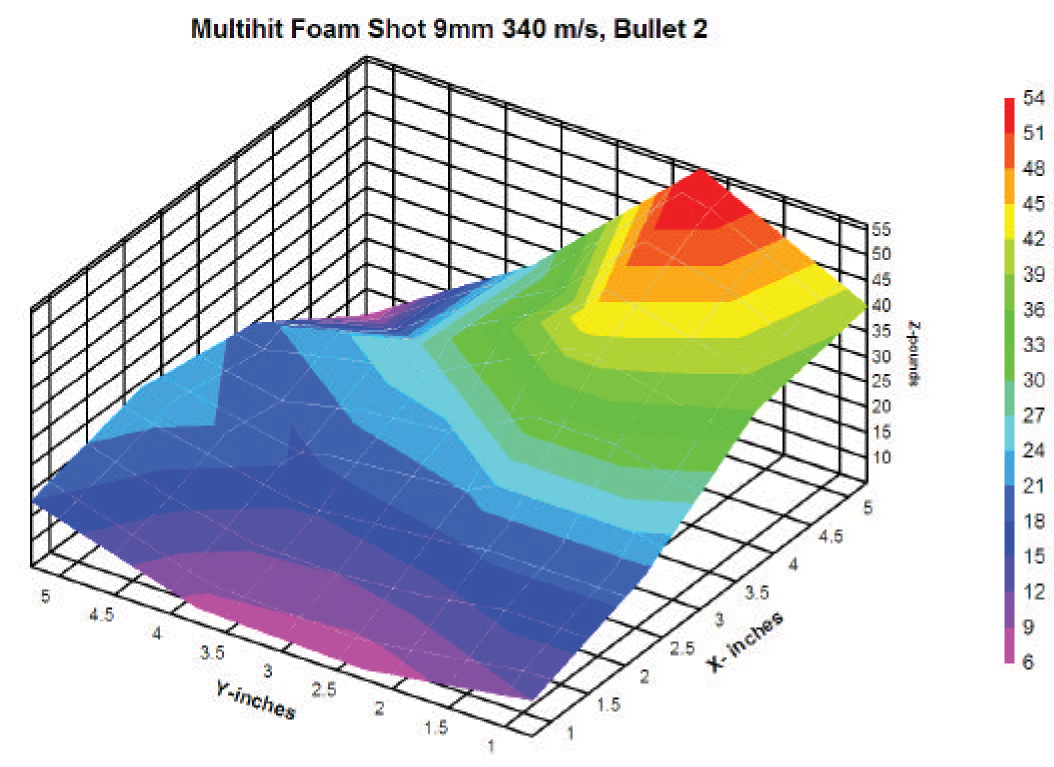


Figure 26: Peak Load Distribution of Foam Backing, Bullet 2 in Figure 22 at 340 m/s

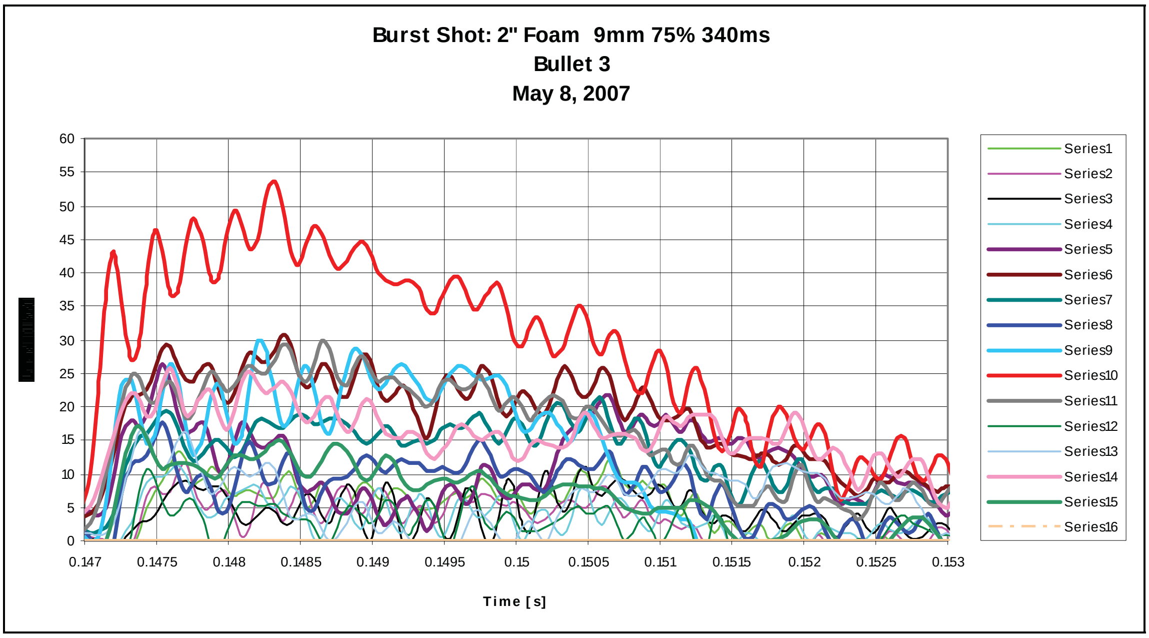


Figure 27: Load Cell Outputs for Bullet 3 for Multi-Hit Test in Figure 22

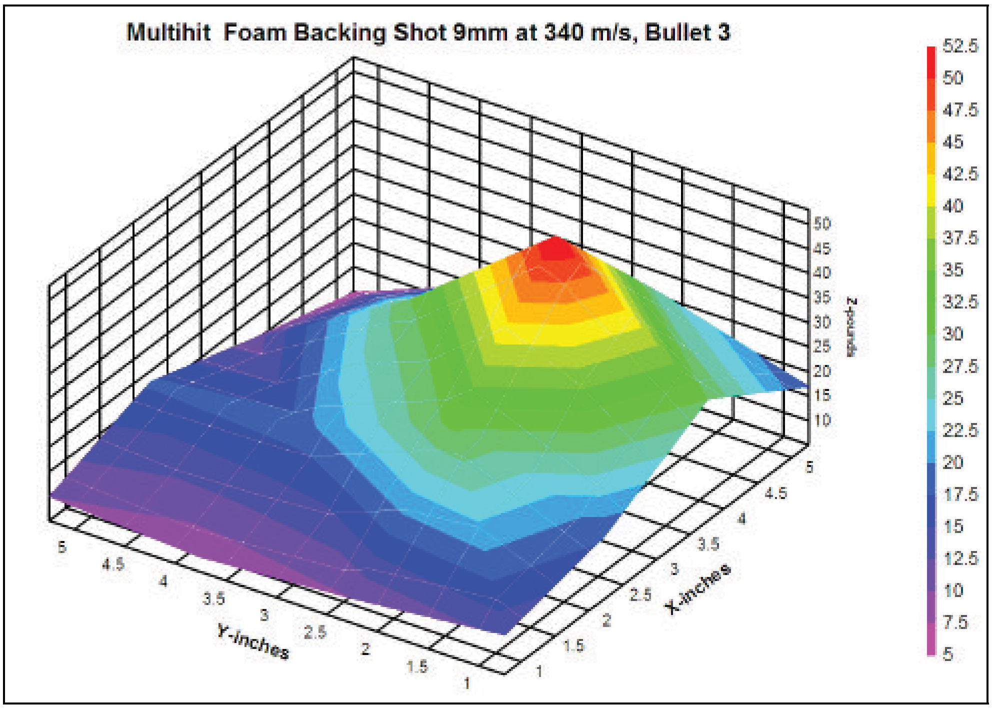


Figure 28: Peak Load Distribution of Foam Backing, Bullet 3 in Figure 22 at 340 m/s

Figure 29: Hard Armour Test Sample

Figure 30: Trauma Depiction from Three Shot Burst

In summary for the clay equivalent investigation the following points are noted:

- The clay equivalent instrumented system was found to be adequately sensitive and the plots of the force distributions were found to be similar in shape to the cavity in the clay. However, it was not possible to arrive at an accurate direct correlation between the clay equivalent and the clay. More investigations are required, possibly utilizing other backing materials, with higher stiffness, that will provide for a flatter load distribution similar to the deformation distribution found in clay indentations.
- Samples of multi-hit testing have shown that the “trauma” consist of three impacts (for the three shot burst), spaced according to the firing rate of the weapon. For 850 rounds per minute, this is spaced at about 71 milliseconds per impact. Each of them acting for duration of about 6 milliseconds. , and may therefore change the way that trauma is assessed in a human. For a single shot, there of course is only one impact which is currently assessed by the depth of indentation in the clay backing.
- From the instrumented foam backed test results, it was noted that the first impact (of a three shot burst) was similar in shape and magnitude as a single shot (as would be expected). The subsequent following two shots are of lower magnitude than the first impact. As a first approximation, the trauma from a multi-hit can be treated as three shots, timed at the firing rate of the weapon, and with each having the force/ time and area distribution of a single shot.

Based on this assumption, the trauma can be taken as the superposition of three cavities, each equivalent to the cavity of a single shot (as can be determined statically) but spaced at the shot pattern used for the multi-hit. See Figure 29 for the depiction of the trauma.

- The system when fully calibrated will have applications for single shot and multi-hit ballistics testing of body without the laborious manual task of working with clay backing.
- More correlating between the foam backed and clay backed results is required at this time to determine the clay equivalent for each shot. Other (then the foam used) backing materials should be considered to give a “flatter” response, using stiffer materials.
- To fully assess the backing materials, and to develop a practical clay equivalent system, if is necessary to have an instrumented plate that covers the whole impact area: about 16 inches x 16 inches in area. Careful consideration will be required for a system that may have more sensors per unit area. Currently, the grid has one sensor per every 1.5 inches square. Future systems may require double that; perhaps one sensor every ¾ of an inch squared. The resulting instrumented plate would have significantly more sensors and require a significantly larger computer and data acquisition system.

Task 7 Multi-Hit Testing of Hard Armour

Because of the brittle nature of hard armour in used in personal vests, it was of interest to determine in a preliminary way the effects of multi-hit testing compared with single shot testing. Personal body armour consisting of a ceramic plate and Kevlar backing was tested with 9mm, .45 ACP, 5.56mm and 7.62mm bullets, both single shot and multi-hit. Foam backing material was use in each case. For all cases, there was significantly more damage to the hard armour during the multi-hit than the single shot. In all cases, the multi-hit penetration velocity was found to be lower than the single shot. Views of sample hard armour and examples of damage are given in Figures 31 and 32.
Table 11 gives the results for the 9mm, 24 grain, FMJRN bullet shots. The single shot carried out using the maximum powder allowed was at 621 m/s and did not result in a penetration of the ceramic armour. Multi-hit tests were carried out at average burst speeds ranging from 580 m/s to 620 m/s all resulted in at least one bullet penetrating the ceramic plate of the armour.

Table 11: Impact Testing of Hard Armour with 9 mm Bullets

Shot Type	Speed (m/s)	Results
Single	621	No penetration of ceramic
Multi-hit	620	One bullet penetration of ceramic
Multi-hit	605	One bullet penetration of ceramic
Multi-hit	580	One bullet penetration of ceramic

Table 12 gives the results for the .45 caliber, 230 grain FMJ RN bullet shots. The single shot carried out using the maximum powder allowed was at 621 m/s and did not result in a penetration of the ceramic armour. Multi-hit tests were carried out at average burst speeds ranging from 554 m/s to 532 m/s all resulted in at least one bullet penetrating the ceramic plate of the armour.

Table 12: Impact Testing of Hard Armour with .45 Caliber Bullets

Shot Type	Speed (m/s)	Results
Single	569	No penetration of ceramic
Multi-hit	554	One bullet penetration of ceramic
Multi-hit	532	One bullet penetration of ceramic

Table 13 gives the results for tests on the hard armour with 5.56 x 45 mm, 50 grain flat base, and hollow point bullets conducted as single shot or multi-hit at 800 rounds per minute. The single shot carried out using the maximum powder loading at about 1100 m/sec did not result in a penetration of the ceramic armour. Multi-hit tests were carried out at average burst speeds ranging from 533 m/s to 1110 m/s. Penetration by at least one bullet resulted in tests where the average speed was about 1000 m/s or more.

Table 13: Impact Testing of Hard Armour with 5.56 x 45 mm Bullets

Shot Type	Speed (m/s)	Results
Single	1100	No penetration of ceramic
Multi-hit	503	No penetration of ceramic
Multi-hit	532	No penetration of ceramic
Multi-hit	588	No penetration of ceramic
Multi-hit	734	No penetration of ceramic
Multi-hit	728	No penetration of ceramic
Multi-hit	965	No penetration of ceramic
Multi-hit	1020	Partial penetration of ceramic
Multi-hit	1083	Partial penetration of ceramic
Multi-hit	1111	Penetration of ceramic

Table 14 gives the results for tests on the hard armour with 7.62mm M80 148 grain bullets. A series of single shots carried out resulted in a determination of a complete penetration V-50 of the hard armour vest at 936 m/s. A multi-hit burst carried out at 700 m/s resulted in a complete penetration also. It is seen, that the multi-hit penetration velocity is significantly (about 24 %) lower than the single shot V-50. The multi-hit test procedure has a significant effect on the performance of hard body armour and should be examined in more detail. Future tests on hard armour should be carried out using the procedures for multi-hit.

Table 14: Impact Testing of Hard Armour with 7.62 mm Bullets

Shot Type	Speed (m/s)	Results (penetration)
Single	850	Partial
Single	858	Partial
Single	898	Partial
Single	928	Complete
Single	919	Partial
Single	922	Partial
Single	925	Complete
Single	924	Partial
Single	934	Partial
Single	932	Partial
Single	950	Partial
Single	947	Complete
Single	**936**	**V-50**
Multi-hit	700	Complete

Figure 31: Sample Undergone .45 Caliber Testing (exterior)

Figure 32: View of Hard Armour Tested with .45 Caliber Bullets

Conclusions and Recommendations

The work conducted herein was successful in developing procedures for testing body armour against a multi-hit threat. Based on the results utilizing the procedures, it was found that penetrations at significantly lower velocities occur with the multi-hit procedures than from the static single shot results of the existing procedures. It confirms the need for dynamic test methods as opposed to static based methods. It is also recommended that more tests be carried out on a variety of body armour designs to ensure that no problems are encountered based on the developed procedure. The foam-faced instrumented backing plate was found to have the necessary sensitivity to measure the “clay equivalent” trauma from the three shot burst. Of particular interest is the three impact trauma, (as opposed to single trauma) that shows in the test results and will require special additional examinations by medical experts. More mathematical modeling and verification testing is recommended to fully define and correlate the outputs from the instrumented backing plate. Based on the limited tests conducted on the hard body armour samples, it was found that the multi-hit procedures, like the soft armour tests, lead to significantly lower penetration velocities. It is recommended that a full procedure developmental program be carried out on the hard armour, leading to a test standard for hard armour.

Acknowledgements

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