Aged Body Armour Testing: Further Results

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Abstract: At the present time, police forces across Canada and USA do not follow any common guidelines on the safe life expectancy of personal body armour because no such guidelines exist. Some forces automatically replace armour at the expiry of the manufacturer's five-year warranty while others extend service life to ten years and beyond. In the absence of meaningful sample selection and proper laboratory testing of aged armour, any degradation of performance may not be detected, leaving the true ballistic resistance of in-service armour largely unknown. The Canadian Association of Chiefs of Police (CACP) and the Ontario Association of Chiefs of Police (OACP) asked the Canadian Police Research Centre (CPRC) to investigate this issue with the intent of developing an Aged Armour Replacement Protocol. This guideline will help to ensure that the body armour worn by police officers is known to be effective.

In support of this effort, police forces across Canada were contacted to determine their body armour procurement, distribution and replacement practices. Numerous participating forces also provided decommissioned body armour to help determine age-related ballistic degradation through laboratory testing. In a previous study [1], 150 NIJ Level II used front panels had been tested at Biokinetics to the NIJ standard indicated on their certification labels. In this paper, ballistic limit tests are presented for the back armour panels of the same 150 NIJ Level II vests. Test results were analysed in light of the observed failure of the NIJ Level II tests executed previously. Furthermore, a second set of 157 NIJ Level II used front panels underwent testing to the NIJ standard indicated on their certification labels. The ballistic results from the second series of armour confirm the trends observed for the first series of armour.

1. INTRODUCTION

1.1 General

Soft body armour is used throughout police forces around the world. These vests are used in a variety of environments (temperature and humidity cycling) that may decrease the ballistic performance of the armour. There is currently no protocol to determine if such degradation occurs and if it is the case, how it should be measured. In an attempt to develop a protocol, armours decommissioned from service were tested [1] using a Vproof procedure that replicated the initial NIJ certification process. In addition to showing no correlations of performance degradation with armour age, these results have shown a surprisingly high rate of failure of the NIJ certified armours even for armours less than 5 years old. Consequently, further efforts were made to verify the observed trends and to further investigate why failure rate was so high**.** The results of this follow-on work are presented herein. The objectives of this paper are to:

a) Assess if there is degradation of armour performance due to aging using further Vproof tests and ballistic limit tests (V50)

b) Investigate the reasons behind the failures of NIJ compliant armours

2. TEST SET-UP AND ARMOUR DESCRIPTION

Data presented herein represents two series of tests using armour samples retired from service within Canadian Police Forces. These two series of tests includes ballistic limit tests executed on 120 matched back panels taken from the first series of 150 armours [1], while the second series of tests were Vproof tests on 157 newly obtained front panels. Both test methods are explained below.

All tests presented were done using the .357 Mag JSP round (158 grains) as specified in the NIJ 0101.03, 0101.04, and interim 2005 standards under threat level II. The armour was placed 5 m from the weapons muzzle.

2.1 Armour sample description

Twenty two police forces across Canada (Alberta, Ontario, Nova Scotia and Saskatchewan) donated soft body armour removed from service. Manufacturer's labels on the samples indicated compliance to standards NIJ-0101.03 [2], NIJ-0101.04 [3] and the NIJ 2005 Interim Standard [4], with a number of samples indicating compliance to "NIJ-0101.03 (To Canadian Testing Procedures)". All armour for which data are reported here were rated NIJ level II. All samples selected for testing were NIJ Type II protecting against 9mm FMJ 8.0 g (124 gr) and .357 magnum JSP 10.2 g (158 gr) handgun rounds. The minimum requirements for the .357 magnum rounds differed slightly at 425 m/s for 0101.03 and 427 m/s for 0101.04 and NIJ 2005 compliant panels. These speeds were indicated on the manufacturer's labels affixed to the armour panels. The age of the armour ranged from 1 to 17 years old. All armours were made from 18 to 35 layers of Aramid.

Data on each supplied sample was collected to determine if there was a correlation between any observed deterioration in armour performance during testing and an environmental factor such as the type of service (e.g., used on foot patrol, bicycle patrol, marine duty, patrol car and so on). However, it was not feasible to obtain complete information on the service history of each garment. In several cases, the front and rear panels obtained from an officer were of different age or had come from different manufacturing batches, and it was not possible to determine whether they had been worn together throughout their entire service period. This type of data was not routinely recorded and by the contributing forces. Ultimately, the relevant data available for all test samples included manufacturer, model, size, date of manufacture and manufacturing lot number, which are included on the manufacturer's labels affixed to the armour inserts. Since the date of retirement was not available, age was defined as the time span from the date of manufacture to the date of the testing, rounded down to the nearest whole year.

2.2 Vproof tests

V proof tests were executed as follows:

a) A triangular shot pattern as described in the NIJ 0101.03, 0101.04 and NIJ 2005 standards for NIJ level II body armour was used, except that all 6 shots were done perpendicular to the body armour (within ± 5°) and all were done with the .357 Magnum JSP round. Shot spacing was 75 mm from any edges and 50 mm minimum from previous shots.
b) All armours were backed with calibrated Roma Plastilina, as per NIJ standard
c) Measurements included impact velocity and backface signature (BFS) for each shot within that impacted the armour within fair range
d) All shots were done at ambient temperature.

Fair velocity ranges for the .357 Magnum are between 425 and 440 m/s for NIJ 0101.03 armours and between 427 and 445 m/s for NIJ 0101.04 and NIJ 2005 armours. Efforts were made to fire the shots at the lowest velocity of the fair range. Due to normal scatter this resulted in some shots below fair and some within fair. This is in contrast to tests done in [1] where shots were attempted within or above the fair range. The reason for this was to investigate armour performance at the minimum stated level of protection.

2.3 Ballistic limit (V50) tests

Ballistic limit tests were done on the back armour samples of the armour tested for Vproof in [1]. In total 120 samples were tested on a total of 150 armours. All armours which front and back armour were not 'matched' were removed from the tests. 'Matched' means front and back panels were made by the same manufacturer, had the same manufacturing date, and similar serial numbers (in most cases, sequential). If there was any doubt that a back panel was matched to the front, it was not included for testing. Ballistic limit tests were executed as follows:

a) The V50 was determined using the methodology defined by MIL-STD 662F [5] which employs the up-and-down method of velocity adjustment to converge on the V50. The V50 was calculated using the arithmetic mean based on six shots. The six shots consisted of an equal number of "highest partial" and "lowest complete" perforation impact velocities within a velocity spread of 45 m/s. Note that in some cases up to ten shots were necessary to achieve this criterion.
b) Backing material used was Minicel® instead of Plastilina to facilitate testing. Limited tests have shown that Minicel® compares favourably with traditional Plastilina clay for V50 testing [6].
c) Shot spacing was 76 mm from any edge and a minimum of 64 mm between shots (Figure 1). The first shot was the topmost point on the armour, and the second and third shots were in the bottom corners. The next shots were directed at the interior dots, spacing them apart from each other as specified.
d) All shots were done at ambient temperature and perpendicular to the armour (within ± 5°)

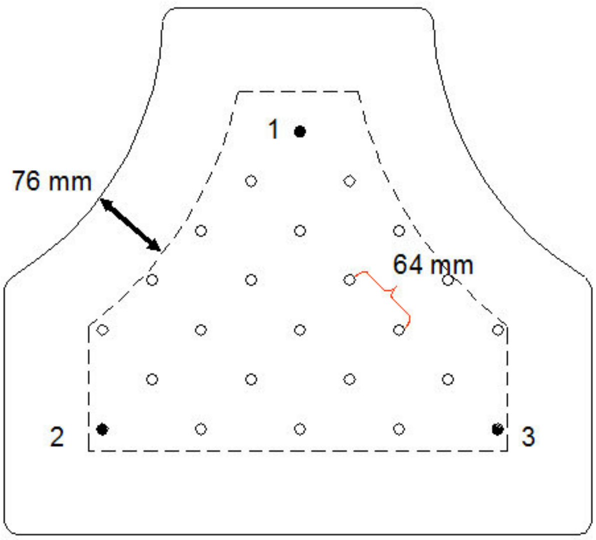

Figure 1 Shot pattern used for V50 tests

3. RESULTS

3.1 Vproof results

Summary of sample characteristics are provided in Table 1. This data show that age composition of the two sample sets were comparable.

Table 1 Age statistics for Vproof tests (years)

Age statistics	Phase 1 [1]	Phase 2
Average	7.9	7.7
Standard deviation (SD)	3.59	4.13

Age statistics	Phase 1 [1]	Phase 2
Maximum	17.6	16.2
Minimum	2.1	1.3
Median	6.6	6.2
Number of samples	150	157

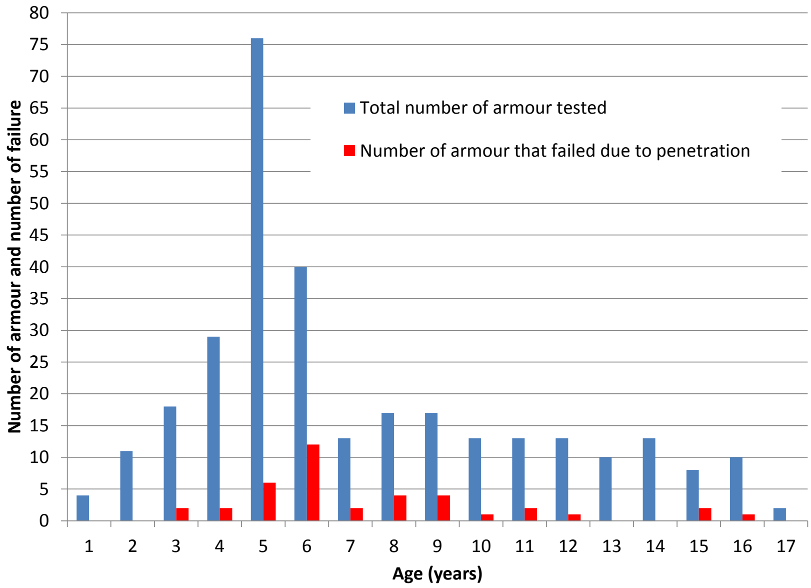

Figure 2 Histogram presenting total number of armour tested with number of perforation failures

Table 2 Statistics of armour failure for both Phases

		NIJ TEST FAIL		PERFORATION FAIL		BFS FAIL	
		Data	CI min/max (95%)	Data	CI min/max (95%)	Data	CI min/max (95%)
TOTAL	Total number of failures	187	55.9/ 67.1	39	9.2/ 16.8	173	51.3/ 62.5
	Proportion of failures	61.5		12.8		56.9	
	Total number of samples tested within or below fair range	304		304		304	
PHASE 1	Total number of failures	107		16		101	
	NIJ 0101.03 failures	95		11		91	
	NIJ 0101.04 & .05 failures	12		5		10	
	Proportion of failures	72.8	65.3/ 79.6	10.9	6.1/ 16.3	68.7	61.2/ 76.2
	Total number of samples tested within or below fair range	147		147		147	
PHASE 2	Total number of failures	80		23		72	
	NIJ 0101.03 failures	67		21		61	
	NIJ 0101.04 & .05 failures	13		2		11	
	Proportion of failure	51.0	43.3/ 58.6	14.6	9.6/ 20.4	45.9	38.2/ 53.5
	Total number of samples tested within or below fair range	157		157		157	

An armour failure histogram of the pooled datasets due to armour perforation or is presented in Figure 2. BFS and NIJ test failures were not pooled because they were statistically different. Summary of failure data for the different samples is presented in Table 2. Failure is defined as a complete perforation at a velocity within the fair range or below. Although perforation failures were similar for the two phases, the BFS failures were higher for the Phase 1 armours; 68.7% in Phase 1 versus 45.9% in Phase 2. The difference observed was statistically significant (at confidence level $p>0.95$ using a binomial confidence interval). Consequently, the observed difference for NIJ test failures was statistically different ($p>0.95$).

More specialized statistics were done for armour perforations within and below fair velocity range. They are presented in Table 3. In agreement with the results presented in [1], perforations did occur at velocities within and below the fair impact velocity range. There is a statistical difference between Phase 1 and 2 in terms of perforation failure for NIJ 04 and 05 armours below and within the impact velocity range.

Table 3 Statistical data for each shot for firings below and within the fair impact velocity range

		Phase 1			Phase 2		
		Qty.	Failure Rate (%)	CI	Qty.	Failure Rate (%)	CI
NIJ 03	Perforations below fair range	1	1.2*	0.0	5	1.9*	0.0
	Number of shots below fair range	83		4.8	262		4.2
	Perforations within fair range	15	5.1*	2.0	17	3.8*	1.8
	Number of shots within fair range	293		8.5	449		6.2
NIJ 04 & 05	Perforations below fair range	3	37.5**	12.5	1	0.8**	0.0
	Number of shots below fair range	8		75.0	129		2.3
	Perforations within fair range	5	15.2***	6.1	2	1.8***	0.0
	Number of shots within fair range	33		27.3	110		4.5

* Confidence interval: 99%
** Statistical difference between Phase 1 and Phase 2 (at confidence level p=95%)
*** Statistical difference between Phase 1 and Phase 2 (at confidence level p=90%)

For armours of different age, failure rates for perforation were compared. Results are shown in Figure 3. These data show that the failure rate varied between 14.5% and 17.5 % at the 95% confidence level. Furthermore, there was no correlation between the failure rate due to perforation and the age of the armours tested ($R^2 = 0.00003$ from linear regression). Similarly, Figure 4 depicts the BFS failure rate as a function of armour age. The failure rate is 61.5% at the 95% confidence level. Once again there is no correlation between failure rate due to BFS and age of the armours tested ($R^2 = 0.08$ from linear regression).

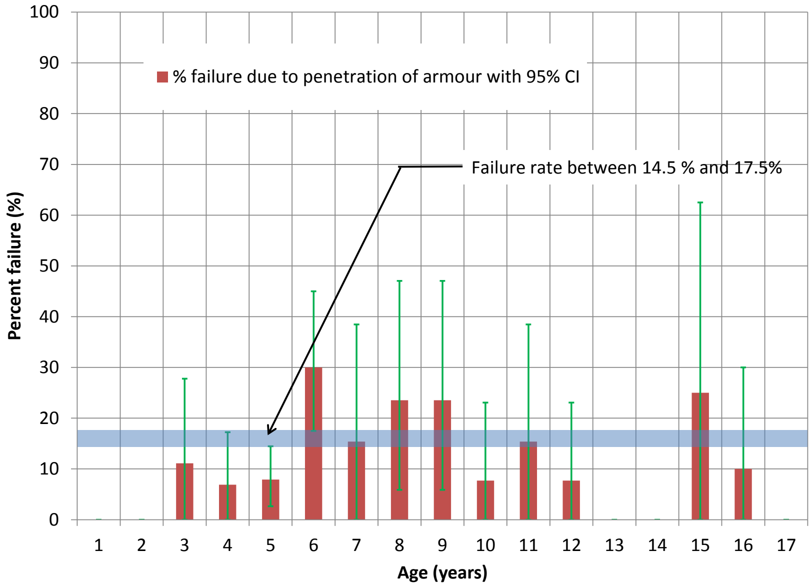

Figure 3 Failure rate for perforation versus age at the 95% confidence interval. Confidence intervals are shown in green for each year.

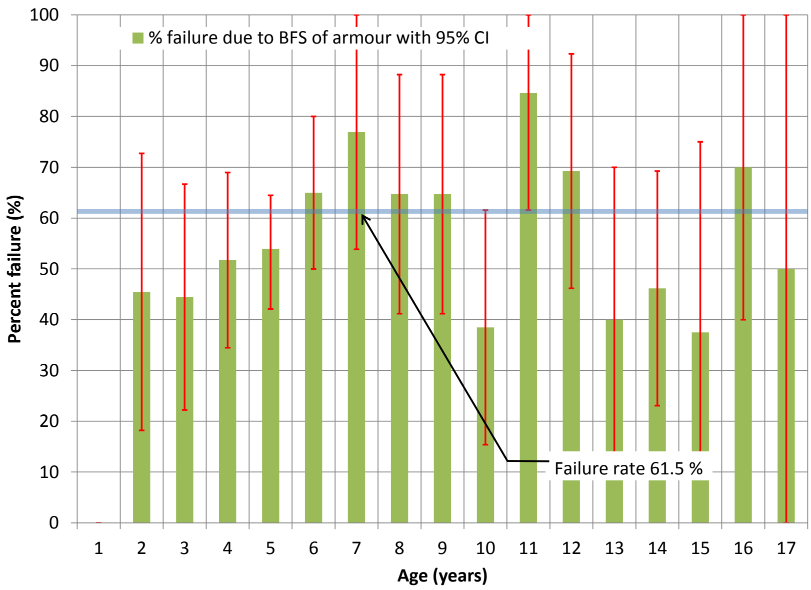

Figure 4 Failure rate for BFS versus age at the 95% confidence interval. Confidence intervals are shown in red for each year.

3.2 V50 results

The perforation failure rates observed were quite high. An analysis of the V50 of the back panel of the armours tested in Phase 1 was therefore executed to understand this phenomenon. Based on the criteria presented above, V50 tests were executed on 120 of the 150 armours available after the Phase 1 Vproof tests (Table 4). The difference between the maximum and minimum measured V50 was 79.6 m/s. This shows the variability of V50 values and therefore an estimate on the variability of the safety margin left by the armour designer. The average error on the measured V50 values was 14.6 m/s.

Table 4 Statistics on the measured 120 V50 values (m/s)

	V50 values measured	SD values measured
Average	479.4	13.9
SD	13.7	3.0
Maximum value	528.8	20.2
Minimum value	449.2	5.9
Average error on V50*	± 14.6	
Maximum error on V50*	± 21.2	
Minimum error on V50*	± 6.2	
Number of armour tested	120	

* At the 95% confidence interval

Analysis of the V50 values with respect to age showed that there was no correlation between the two variables ($R^2 = 0.0028$ from linear regression). Furthermore, analysis of the armours by police forces and by manufacturers have not shown correlation with age either.

4. DISCUSSION

4.1 Variation of performance versus age of the armour

Our results have clearly shown that there were no correlations between the armour age and the variations of performance using either V50 testing or Vproof testing. One explanation is that the variation in make, manufacturer and police force requirements are quite large, although they all claim certification to some version of NIJ Level II. An attempt to refine the process by selecting data applicable to a single manufacturer or for one particular police force did not show any trends. Analysis of the Vproof data for Phase 2 confirms the observations that were made in Phase 1 with regard to perforation failures of NIJ compliant armours. Surprisingly, BFS failures are statistically higher for Phase 1 compared to Phase 2. Reasons for this are unknown.

The ideal process to assess armour aging would be to ensure that additional armours are purchased during the acquisition process. Those additional armours would be used to provide baseline performance data (year 0) as well as performance data after being worn and used by police officers (e.g., year 5). Another process might be to approach the armour manufacturer that built the vests used in this study and to trace back their quality control datasheets. These data would be considered baseline data that could then be compared with the test results presented herein. This would be a challenging task as some armour manufacturers have been bought by other armour manufacturers or have simply gone out of business. Furthermore, armour manufacturers might be reluctant to provide quality control data for liability reasons.

A third possibility would be to acquire brand new armours similar to those tested with the same design and manufacturer and to test them through a V50 procedure. Those V50 values would then be compared to naturally aged armours data. This again would provide a good indication of correlation although it is never certain that the observed difference, if any, would be caused by batch to batch variations or by slight improvements of weaving techniques, for example.

4.2 Investigation concerning observed failure of NIJ certified armours

Testing has resulted in perforations in armours that claim to have passed the standard requirements even after only 2 or 3 years. This raises the question: Why are there so many failures at re-test of the armour?

Analysis of the number of shots required to pass the NIJ 0101.03 [2] and NIJ 0101.04 [3] standards shows weaknesses in the methodology that resulted in very low statistical confidence of the verification process under these standards. This low statistical confidence comes from a low number of shots being used to assess the ballistic limit of the armour. Therefore, the test standards would seem to allow for acceptance of armour largely influence by chance. Both of these older standards assume that the velocity bracket will correspond to a very low probability of perforation, but given that the verification is not statistically valid, it is possible that the probability of perforation within the velocity bracket is much higher than expected.

Recognition of the lower statistical power of the previous NIJ standards is shown in the most recent version of the NIJ standard (NIJ 0101.06, [7]), where the statistical sampling has been increased significantly for BFS and ballistic limit tests, as presented in Table 5. For completeness, the calculated confidence level for 5% perforation probability is calculated for each version of the standard, i.e. the probability to obtain one or more failures over N trials if Pf, the single-shot probability of failure, were 5%. It shows that for the NIJ 0101.06, the confidence that the probability of perforation is 5% or less is 81%, whereas it is much less for the other versions. Based on this information, it is possible that some of the armours tested in this paper would not have passed the more rigorous test methodology in the most recent NIJ standard even if they had been brand new.

Table 5 Statistical sampling and associated confidence level for each NIJ standard version

	BFS tests		Ballistic limit tests
Standard	Allowed number of perforations per number of shots, for perpendicular impacts	Calculated confidence level for 5% perforation probability	Number of shots used to calculate ballistic limit
NIJ 0101.03	0/8 shots	34%	N/A
NIJ 0101.04	0/16 shots	56%	12
NIJ 0101.06	0/32 shots	81%	120

For financial, weight and flexibility reasons, it is more advantageous for manufacturers to reduce the safety margin between the ballistic limit of the armour and the impact velocity fair range in order to keep the number of armour layers to a minimum and thus remain competitive. This fact drives manufacturers to build armours that barely pass the standard. In addition, all approved armours are certified for the standard without clearly stating if they were tested at the lower or the upper end of the allowed velocity bracket. This makes a significant difference in terms of the probability of perforation and could result in failure of the armour if a retest were to be carried out. The NIJ 0101.06 standard recognizes this issue by specifying that the velocity bracket within which the perforation tests occur corresponds to a maximum of 5% perforation probability based on a statistically sound ballistic limit test performed using 120 shots.

Nevertheless, the lowest speed of perforation recorded was 417 m/s. In the newest version of the standard, NIJ-0101.06, armour is subjected to environmental conditioning effects of heat, humidity and mechanical tumbling. The intention is to expose weaknesses in ballistic materials that would suffer from these effects, similar to officer usage over time. The ballistic fair velocity range for conditioned armour in NIJ-0101.06 is relaxed to be 399 to 417 m/s. Therefore the lowest speed of perforation in these Vproof tests falls just at the outer limit of the NIJ-0101.06 requirements for conditioned armour.

5. CONCLUSIONS

Despite important performance differences between armour lots, no correlations were found between the age of the armour and its ballistic performance, either in terms of ballistic limit or failure rate. Investigation as to why so many armours were failing a retest following the NIJ standard have shown that sample size played a role in the process, resulting in certifying some armour based more on chance than on genuine performance.

6. WAY AHEAD

This study might have been affected by many uncontrolled variables: samples from many sources, different material, variability of service use, sample from different manufacturers, etc. In order to mitigate these effects, a batch of 7 years old armours from one manufacturer and from the same lot as identified (name hereafter naturally aged armours). A total of 100 new armours made from the same manufacturer with the same material will be acquired. For direct comparison, V50 tests on the 50 naturally aged armours will be compared to V50 tests on 50 new armours and 50 new armours environmentally degraded as specified in NIJ 0101.06 standard. This will reduce the effect of some variables concerning aging degradation and will enable the assessment of environmental degradation described in NIJ 0101.06 standard.

7. REFERENCES

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