Update of the body armour purchase and replacement protocol

Final project report

Christopher Withnall
Biokinetics and Associates Ltd.
2470 Don Reid Drive
Ottawa, ON
K1H 1E1

Laurin Garland
Vernac Ltd.
2193 Peter Robinson Rd.
Carp, ON
K0A 1L0

Prepared By:
Biokinetics reference R13-22

PWGSC Contract Number: W7701-61933/001/QCL
Contract Scientific Authority: Daniel Bourget, Defence Scientist, (418) 844-4000 Ext. 4228

Contract Report
DRDC-RDDC-2014-C206
October 2014

Abstract

Several research programs have been undertaken in recent years to investigate the performance of aged soft body armour used by Canadian police forces. The original aim of this work was originally to inform police about the suitability of in-service armour, but it became rapidly clear that any system of checking aged armour would require starting with good quality new armour of known performance. Testing of field-returned body armour revealed many unexpected situations where armour allowed bullet perforations at standard velocities. In the meantime, the latest version of the ballistic body armour standard, NIJ-0101.06 was released in 2008, introducing a higher degree of design and production consistency in body armour. Based on elements from this most recent version of the ballistic standard, a method for further ensuring production quality has been proposed via a lot acceptance test, followed in the future by an aged armour test against that lot. Practitioners of this protocol will enjoy reassurance that they have supplied their officers with quality products. They may further enjoy economic benefit by extending the use of that armour into the future, provided it passes laboratory testing.

This page intentionally left blank.

Executive summary

Update of the body armour purchase and replacement protocol: Final project report

To date there has been no accepted practice to determine if and when body armour ballistic performance has degraded to a level that will no longer provide an officer adequate protection. Replacement policies range from five years to indefinite service life. The ballistic capability of aged armour is not well understood, so the former Canadian Police Research Centre (CPRC) sponsored a program, beginning in 2007, to develop an aged armour replacement protocol.

The development of the protocol was in response to a request to the CPRC from the Canadian Association of Chiefs of Police (CACP) "to investigate the issue of life expectancy of soft body armour with respect to issues including the manufacturer's warranty period and replacement time". In addition to the foregoing, the Ontario Association of Chiefs of Police (OACP) requested that CPRC become involved in a research project to investigate "the degradation of ballistic armour material over time" by carrying out a program which would "test body armour in a consistent scientific manner". The OACP volunteered to assist where possible in arranging for the supply of aged armour from Ontario police services to use as test samples.

Biokinetics and Associates Ltd was contracted through DRDC Valcartier on behalf of the CPRC to obtain and test samples of aged soft body armour which had been retired from active duty with police services across Canada and to carry out appropriate ballistic tests to determine whether the performance of the armour had deteriorated with age. All ballistic testing was conducted at Biokinetics' facility in Ottawa, Ontario.

Following a background study to investigate manufacturers' warranties and armour purchasing, use and replacement policies among Canadian police services, a three phase test program was completed totalling 450 samples of field-returned armour ranging from 1-19 years old. Ballistic tests were carried out according to an abbreviated version of the National Institute of Justice standard to which a bullet resistant panel was originally certified. All tested panels had been originally certified to some version of NIJ-0101, Level II performance. The majority of tests were conducted at the low end or within the range of fair bullet velocities for certification, all ambient and at zero degree obliquity. A number of perforations experienced within this test series at various ages of armour suggested that age was a lesser determinant for bullet resistance than design and construction.

Additionally, a test program was carried out to investigate the V50 performance of armour rear panels matched to the front panels used in the aged perforation testing and another was completed to look at the effect on measured V50 performance of using the typical clay backing material versus using a foam Minicel® material. Finally, a test program (funded through TSWG) looked at the procedures implemented in the most recent NIJ-0101.06 standard to compare results obtained through ballistic tests on field aged armour vs. new armour conditioned per the NIJ methodology. Results of these tests cast doubt on the efficacy of V50 as a measure of aged armour performance, and confirmed that standard clay ballistic backing procedures were preferred.

Following the initial series of ballistic tests, an aged armour replacement protocol had been drafted with a plan to update that draft when the complete series of tests was finished. It was reconciled that any protocol to ensure the ballistic resistance of body armour must start with new and fully checked armour and follow with tracking and future testing to determine continued service life. There was no way to test existing samples of in-service armour as an indicator of future service life.

Much has been learned during the overall five year program and some initial assumptions about the ballistic performance of both new and aged body armour have been found incorrect. Further, considerable insight has been gained into test methodologies and how best to represent the performance of aged armour for a replacement strategy based on scientific evidence and consistent testing. In this current program the results of this prior work are compiled in a single document for ease of review and a revised protocol is outlined.

The revised Body Armour Purchase and Replacement Protocol is based upon acceptance testing a sample from every purchase lot of armour and then conducting similar tests on aged samples pulled from service in future years. Prior to a police service electing to follow the protocol, there are a number of factors which will need to be considered, both financial and otherwise. There are some obvious costs, such as the purchase of additional armour to replace that selected for testing and the cost of that testing, however, there are also some potential savings, such as the decrease in life cycle cost due to safely extending the in-service period for a batch of body armour. In addition to the financial considerations, there are other factors influencing a decision regarding implementation of the protocol. These might include, for example, any policies already in force which bear on armour replacement such as a mandated five year replacement.

In the process of finalizing the protocol, much consideration was given to determination of test sample selection as this is a major factor not only in protocol implementation costs, but more importantly in the scientific validity of the use of the protocol. In order for test results from a sample of any product to be used to predict the performance of the rest of a purchase lot of that same product, the sample must be representative of the purchase lot and must be selected randomly from it. Acceptance sampling uses statistical methods to determine whether to accept or reject a production lot of material. It has been a common quality inspection technique used in industry. The aim is to determine the acceptance of a production lot based on the inspection of a small sample from that lot. Correct determination of sample size has been the result of much study but requires further discussion and the blessing of policy makers to accept the risk levels proposed. The same approach as proposed for acceptance testing of a new lot of armour is proposed for repeated testing of aged amour. A representative sample is drawn back from service and tested to a modified NIJ methodology. If the sample shows no failures, the remainder of that purchase lot continues in service for another year, at which point testing is repeated on another sample. Any perforation of any armour in the sample during the testing results in retirement from service of the remainder of the purchase lot.

This protocol is intended to provide a foundation for further discussion among manufacturers, purchasers and users of personal ballistic body armour.

Table of contents

List of figures

List of tables

1 Consolidation of DRDC Aged Armour Programs

1.1 Background of Aged Armour Programs (2007-2012)

It is unclear what may be the "safe" life expectancy of ballistic body armour worn by Canadian police officers. To date there has been no accepted practice to determine if and when body armour ballistic performance has degraded to a level that will no longer provide an officer adequate protection. Replacement policies range from five years (to coincide with the typical manufacturer's workmanship warranty) to indefinite service life, replacing a vest only after obvious physical damage, a sizing change requirement, or an officer's departure from service. The ballistic capability of aged armour is not well understood, so the Canadian Police Research Centre (CPRC)[1] sponsored a program, beginning in 2007, to develop an aged armour replacement protocol.

The development of the protocol was in response to a request to the CPRC from the Canadian Association of Chiefs of Police (CACP) "to investigate the issue of life expectancy of soft body armour with respect to issues including the manufacturer's warranty period and replacement time".

In addition to the foregoing, the Ontario Association of Chiefs of Police (OACP) requested CPRC become involved in a research project to investigate "the degradation of ballistic armour material over time" by carrying out a three year program which would "test body armour in a consistent scientific manner". The OACP volunteered to assist where possible in arranging for the supply of aged armour from Ontario police services to use as test samples.

Biokinetics and Associates Ltd was contracted through DRDC Valcartier on behalf of the CPRC to obtain and test samples of aged soft body armour which had been retired from active duty with police services across Canada and to carry out appropriate ballistic tests to determine whether the performance of the armour had deteriorated with age. A subcontract was issued to Vernac Ltd. to familiarize the police forces with this program as well as to request aged armour for testing and participate in the analysis and presentation of test data. All ballistic testing was conducted at Biokinetics' facility in Ottawa, ON.

Following a background study to investigate manufacturers' warranties and armour purchasing, use and replacement policies among Canadian police services (Biokinetics report R07-16), an initial Phase I test program was completed on 150 samples of field-returned armour. This program was described in Biokinetics report R09-28 (DRDC report CR 2010-117). Ballistic tests were carried out according to an abbreviated version of the National Institute of Justice standard to which a bullet resistant panel was originally certified. All tested panels had been originally certified to some version of NIJ-0101, for Type II performance to protect against 9 mm and .357 test rounds. As a consequence of the initial results, the report concluded in part as follows: "Further testing of aged armour should continue with target speed centred on the minimum allowable speed. In this fashion, some shots will be too slow and some within the low end of the fair range. Any penetrations in this regime will be a more solid indicator of an armour's true aged performance as related to officer safety."

---

[1] The CPRC has since been combined with two other security research programs, CRTI and PSTP, into the Canadian Safety and Security Program of the Centre for Security Science.

The Phase II tests on another 150 samples of aged armour followed this modified protocol and were carried out using only .357 rounds, since the initial test series showed no perforations with the 9 mm ammunition. The second test series is the subject of Biokinetics report R11-12.

Finally, the Phase III test series followed the same procedures as Phase II, with bullet speeds centred on the low end of the fair range as this was felt to be the data of most direct interest to the twenty three Canadian police services who had contributed the armour. The results of that series of tests, combined with the test results from all 450 samples, were reported on in Biokinetics report R12-11.

Additionally, a test program was carried out to investigate the V50 performance of armour rear panels matched to the front panels used in the Phase I tests (report R11-07), and another was completed to look at the effect on measured V50 performance of using the typical clay backing material versus using a foam Minicel® material (report R12-12). Finally, a test program (funded through the Technical Support Working Group (TSWG)) looked at the procedures implemented in the most recent NIJ-0101.06 standard to compare results obtained through ballistic tests on field aged armour vs new armour conditioned per the NIJ methodology (report R12-19).

Following the initial series of ballistic tests, a draft aged armour replacement protocol was developed (report R10-06) with a view to updating that draft when the complete series of tests was finished.

Much has been learned during the overall five year program and some initial assumptions about the ballistic performance of both new and aged body armour have been found incorrect. Further, considerable insight has been gained into test methodologies and how best to represent the performance of aged armour for a replacement strategy based on scientific evidence and consistent testing.

In order to address the initial concerns which formed the basis for the series of programs, the following sections compile the rationales, testing procedures and results of these multiple programs into a single document.

1.2 Thumbnails of Prior Program Reports

To date there have been a total of seven aged armour related programs sponsored by CPRC through DRDC and one sponsored by TSWG, spanning 2007 to 2012. A list of project reports and brief description is provided below listed in chronological order.

R07-16 Development of an Aged Armour Replacement Protocol: This was an introduction to the issues associated with developing a replacement protocol. The US Office of Law Enforcement Standards (OLES) response to the Zylon® degradation issue was summarized. The meaning of manufacturer warranty was investigated, the availability of aged armour was researched and a workplan was conceived to move forward with the securement and testing of aged armour from Canadian police forces.

R09-28 (rev 3) Aged Armour Testing Study - Report on Results of 150 Samples: Ballistic testing was carried out on 150 samples of used soft body armour ranging from 2-17 years old submitted from twenty different Canadian police forces. The aim was to investigate the performance of aged body armour to provide a scientific basis for an aged armour replacement protocol. Products displaying good performance at 13-17 years and others failing at 3 years suggested that the initial design and construction of body armour might play a greater role in bullet resistance than simple aging.

R10-06 Development of an Aged Armour Replacement Protocol: A protocol was outlined that was prospective, and included batch acceptance testing at the time of new armour purchase as well as subsequent testing at future time intervals. Guidelines for determining the continued serviceability of aged armour were put forth based largely on allowable degradation of environmentally conditioned armour in the latest NIJ-0101.06. Further guidelines were presented for quantity sample selection based on ISO 2859-1 inspection models.

R11-07 V50 Testing of Aged Body Armour - Report on Results of 120 Samples: Back panels that were matched to front panels from R09-28 were tested in a 6-shot V50 methodology to increase confidence in the dataset. Testing was done using Minicel® foam backing rather than clay. After review of the data, this change was strongly suspected to have influenced the results.

R11-12 Aged Armour Testing Study – Phase II, Report on Results of a 2nd Set of 150 Samples: This was a continuation of testing begun in R09-28. P-BFS tests were carried out on an additional 150 front panels. However bullet speeds were centered at the low end of the fair speed range. Results were very similar to previous, and the same conclusion held that age alone did not appear to be correlated with ballistic resistance.

R12-11 Aged Armour Testing Study – Phase III, Results of Ballistic Tests on 450 Samples: This was a continuation of testing field returned aged armour described in R11-12. Bullet speeds continued to be centered at the low end of the fair range, the area most interesting for officer safety. Overall results from previous phases remained unchanged, and age alone did not correlate well with ballistic performance. The increase in data base size provided a high degree of confidence in the conclusions.

R12-12 Aged Armour: Investigation of Clay vs. Minicel® Backing Material - Report on Results of 50 Samples: Fifty rear armour panels were selected from the Phase II and Phase III supply. These were of the same make and model and as identical in terms of mean age and size as possible then divided into two 'equivalent' sets of 25 panels each. One set was tested for V50 on Minicel® and the other on traditional clay. Differences in the overall V50 confirmed the discrepancies observed in R11-07.

R12-19 V50 Testing of Aged Armour Compared with NIJ-0101.06 Environmentally Conditioned Armour: This program was funded by the Technical Support Working Group (TSWG) through DRDC-Valcartier. Fifty aged armour panels made by one manufacturer to a particular specification were supplied by one police service. One hundred panels made by that manufacturer to the same specification were purchased new. Half the new panels were exposed to the NIJ-0101.06 environmental conditioning process. V50 tests were carried out on the new, aged and conditioned groups and the results compared. Results showed differences in the V50 scores, as well as the shapes of the logist curves, which may influence the choice of V50 as a test methodology in a replacement protocol.

1.3 Consolidation of Data and Findings

For convenience the collection of program reports listed in Section 1.2 will be consolidated into four general topics, including the background work introducing issues that justify the development of a protocol, the findings from P-BFS testing on 450 panels, the V50 testing using Minicel® foam comparison against clay and the V50 testing on aged vs new-conditioned armour.

Discussion about the draft aged armour replacement protocol and what parts of it require updating will be covered in Section 2.

The objective of this is to provide a single document of reference to justify the approach taken in updating the protocol.

1.3.1 Background Issues Justifying the Need for a Replacement Protocol

As an initial step in a program to develop a replacement protocol for aged soft body armour, Biokinetics was contracted to investigate the current policies and practices of body armour manufacturers and Canadian police services as well as other matters relating to a potential test program. This involved reviews of the following:

- NIJ previous work in the area,
- Current warranty practices of body armour manufacturers,
- Current armour replacement policies of Canadian police services,
- Availability of used soft body armour for testing,

1.3.1.1 NIJ Previous Research into Aged Armour Performance

Because of the 2003 Forest Hills shooting and resulting injury of an officer wearing a vest made of Zylon®, which was designed to defeat the round with which the officer was shot, the NIJ entered into a multi-year program of laboratory investigation of aged armour, limited testing on field returned aged armour and additional applied research. A major conclusion of this work was that the performance of Zylon® armour will degrade significantly if it is exposed to elevated temperatures and humidity.

The outcome was the development and issuance in 2008 of a new version of the NIJ standard which governs the performance of body armour, NIJ-0101. This most recent version, NIJ-0101.06 included for the first time an environmental conditioning protocol which attempted to replicate the effect of natural aging[2].

The NIJ prefers the term "environmental conditioning" because there is no way definitively to correlate artificial with real aging. The aim is to reproduce some sort of physical, hydrolytic and temperature fatigue in armour. The current standard includes tumbling, folding and ultra-high humidity exposure within a controlled environmental chamber. What remains unclear is that accelerated exposure to these elements affects ballistic fibres in the same manner as the longer term general use.

What also remains unclear is how ballistic materials other than Zylon® will react to artificial aging, or environmental conditioning. So far, the NIJ's research has centred on Zylon®, since that was the material that failed in Forest Hills. We do not know how the NIJ research, focused on Zylon®, will translate to other materials. Manufacturers of other ballistic fibres, such as DuPont (Kevlar®), Honeywell (Spectra®), and DSM (Dyneema®) have reported on their own tests for degradation and aging, but these can only be completely credible if confirmed independently.

---

[2] This standard had not been issued at the time of that reporting. However, we had been given a copy for review and comment. The standard was issued essentially in the same form.

1.3.1.2 Manufacturer Warranty and Replacement Issues

We conducted an informal poll of six manufacturers of body armour, focusing on a combination of Canadian and international suppliers. The terms of warranty varied among manufacturers, some explicitly identifying only materials and construction, others implying that ballistic performance was guaranteed for the duration of the warranty period. One manufacturer actually offered a sizeable insurance sum should their product fail. With the exception of one manufacturer, who candidly indicated that their client did not require a warranty, the ubiquitous five year warranty period was clearly evident.

What was also evident, even among this small sample, was the wide range of ballistic materials that were used. These included Kevlar®, Dyneema®, Twaron®, Goldflex (Spectra®) and Zylon®. We know about Zylon®'s recent extensive study by the NIJ, but the potential degradation of the others remains unclear.

Note that these warranty issues have since undergone significant change by manufacturers now certifying to the latest NIJ-0101.06. See Section 4.1.2 for more discussion.

1.3.1.3 Police Armour Replacement Practices

We obtained vest replacement intervals from several major Canadian police forces[3]. Only one force conducted routine ballistic tests on samples of their aged armour, and found, as a result, that approximately seven years was the typical replacement interval. Other forces adopted a ten year replacement interval, and further mentioned that older armour is assigned to officers who must have it because of policy, but will unlikely ever use or need it. One adopted a ten year cycle based on informal non-standardized tests using service weapons in firing ranges. Forces that simply adopted a five year cycle appeared not to do any tests. Some forces had no replacement policy. What was clear from this informal poll was that there was no common protocol for the replacement of aged armour. Those forces that adopted a simple five year policy might be discarding serviceable armour prematurely. Those forces extending service life to ten years might not be selecting an appropriate statistical sample such that their tests reflect the population of users.

1.3.1.4 Available Armour Database

We contacted the largest Canadian police forces, using both the RCMP Pay Council Comparator Universe and the Canadian Centre for Justice Statistics "Police Resources in Canada, 2007" to select them. The number of sworn officers represented by these cities accounted for 67% of the total officers in Canada.

Details on the quantities and makes of armour, as well as their other details on warranty issues, were collected. The estimates of the body amours in the various police forces compared very favourably with the published statistics on officer numbers.

What were surprising, however, were the relatively low estimates on the quantities of used armour that could be made available for study. Granted these were very rough estimates, based on informal telephone conversations, and some forces did not have numbers available at that moment, but we only confirmed fewer than 100 aged armours available for testing. Even by

---

[3] Note that this section reports on the details reported in 2007. We have recently heard reports that many large Canadian police forces are changing their armour replacement policies (2014).

conservative estimates, assuming that one in ten vests is replaced annually, that should have made available over four thousand aged armours removed from service each year.

Note that during the resulting test program, we had excellent response from 23 police services which provided us with over 450 complete sets of body armour, more than sufficient for the test program.

1.3.1.5 Background Review Conclusions

1. There is no standardized rationale or protocol for replacement of aged body armour in Canadian police services.

2. Warranty alone is not a valid rationale for replacement at a given interval, as warranty terms do not necessarily include ballistic performance over the period.

1.3.2 P-BFS Data on 450 Field-Returned Armour Samples

Samples of decommissioned body armour were solicited from Canadian police forces and tested according to an abbreviated version of the National Institute of Justice protocol to which they were originally certified. Twenty three forces supplied 450 sets of soft body armour. Manufacturer's labels on the samples tested indicated compliance to standards NIJ-0101.03 and NIJ-0101.04.

All samples accepted for this program were NIJ Type II protecting against 9 mm FMJ 8.0 g (124 gr) and .357 magnum JSP 10.2 g (158 gr) handgun rounds within specific speed ranges called "fair". A product must stop the round within this fair speed range to be certified. Minimum speeds for the 9 mm were the same in both .03 and .04 compliant samples, at 358 m/s. The minimum requirements for the .357 magnum rounds differed slightly at 425 m/s for NIJ-0101.03 and 427 m/s for NIJ-0101.04 compliant panels. Several key pieces of information relating to service history and usage were requested in an effort to correlate environmental factors with ballistic performance, but unfortunately such information was unavailable.

Data on three program phases are combined in this summary report. During the initial Phase I testing of 150 panels, complete perforations at fair speed or lower with .357 rounds occurred in 19 panels (13%), three of which (2%) were at speeds below the minimum allowable. There were no perforations with 9 mm rounds at fair speed or lower. (Biokinetics report R09-28, DRDC report CR 2010-117)

As a consequence of the initial results, the report concluded in part as follows: "Further testing of aged armour should continue with target speed centred on the minimum allowable speed. In this fashion, some shots will be too slow and some within the low end of the fair range. Any penetrations in this regime will be a more solid indicator of the armour's true aged performance as related to officer safety."

The Phase II tests on another 150 samples of aged armour followed this modified protocol and were carried out using only .357 rounds, since the initial test series showed no perforations with the 9 mm ammunition, (Biokinetics report R11-12).

Finally, the Phase III test series followed the same procedures as Phase II, with bullet speeds centred on the low end of the fair range as this was felt to be the data of most direct interest to the police services who had contributed the armour. The Phase III report combines the test results from all 450 samples, (Biokinetics Report R12-11).

During the combined Phase I, II and III testing, perforations at fair speed with .357 rounds occurred in 56 panels (12%), and at speeds below the minimum allowable in 20 panels (4%). However, if these results are considered in terms of the most recent NIJ 0101.06 standard where a degradation margin is allowed for performance of conditioned armour, only three of these perforations in naturally conditioned armour would be considered failures (1.4%).

For combined Phases I, II and III, our tested panels ranged from 1 to 19 years old. Perforations below minimum speed occurred with panels as young as 3 years. In this dataset, therefore, age does not appear to correlate with ballistic performance. However, the samples upon which these observations were made are not necessarily representative of current in-service armour.

1.3.2.1 Armour Age Statistics

The age statistics for the Phase I, II and III testing are provided below in Table 1. The first two aged armour groupings are very similar in terms of age range, average age and median age. The Phase I and II groups each span a range of 15 years (2-17 years and 1-16 years respectively). The third group averages approximately 2.5 years older and spans a wider range of 17 years (2-19 years). Age calculations count the months from the date of manufacture to the date of testing, but they are subsequently reported in years by dividing by twelve and reporting the integer value only. This is similar to a person's age where the last fractional year is not counted until their birthday.

Table 1: Age statistics for Phase I and Phase II armour.

Age statistics*	Phase I	Phase II	Phase II	Combined
mean (months):	94.5	92.3	123.8	103.5
mean (years):	7.4	7.3	9.9	8.2
stdev (years):	3.60	4.16	5.41	4.6
max (years)	17	16	19	19
min (years)	2	1	2	1
median (years)	6.0	6.0	8.0	6.0

(* years calculations based on the integer value of age)

1.3.2.2 Target Speeds and "Fair Velocity"

All testing in this series was of Type II soft body armour meant to meet either the NIJ-0101.03 or .04 standards. Because it is not possible to fire a bullet at a precise speed, the two versions of the standard allow an acceptable test speed range deemed "fair". A "fair hit" is one where the bullet was traveling within this acceptable speed range. Above the fair speed, a panel might still stop a bullet, but any perforation is not deemed a failure and a retest is done. When testing according to the standard a bullet moving within fair speed range and below must not perforate.

NIJ-0101.03 references a Minimum Required Bullet Velocity of 425 m/s, and defines a fair hit as "an impact velocity no more than 50 ft (15 m) per second greater than the minimum required test velocity". This gives a .357 range of 425 to 440 m/s, but the defining velocity is the minimum 425 m/s, not some higher reference number.

NIJ-0101.04 on the other hand defines a reference velocity plus or minus a tolerance. For .357 this is 436 ± 9.1 m/s or in other words from 427 to 445 m/s.

A similar distinction in the definition of fair speeds for 9 mm projectiles exists between the standards.

1.3.2.3 Overspeed Tests

During Phase I, we introduced the concept of the 'overspeed' test. The idea was that if armour was indeed degrading over time, a failing V-proof test would only tell you that it had degraded to an unacceptable level. However, testing above the V-proof speed could act as an 'early warning' indicator.

We first set an overspeed of 10% for both rounds, but found that every .357 at this overspeed would perforate, but not any 9 mm's. Consultation with the OLES revealed that this was not unexpected, and it was recommended to reduce the .357 overspeed to 5%, and increase the 9 mm overspeed to 15% to get closer to their respective perforation limits.

1.3.2.4 Back Face Signature

Back face signature (BFS) refers to the depth of the depression in the clay backing material upon which the panel is positioned when fired upon. The clay is smoothed and planed level with the outer box frame before testing, and it is against this initial flat surface that the depth is referenced. In standard testing, 44 mm is the maximum allowable depth of indentation, even in cases where the projectile does not perforate. We measured BFS for the standard speed .357 projectiles, but not for the standard speed 9 mm. The 9 mm bullets were excluded because having lesser mass and speed they always created a lesser indentation than the .357s.

While the BFS bears some relation to injury risk in humans, it is projectile perforation that is of primary interest to this study. Although BFS is a requirement for new armour, it is generally accepted that aged armour will have "softened up" over time with repeated flexing in use and that an increased BFS measurement may not be cause for alarm. Indeed, in NIJ-0101.06, excessive BFS measurements do not constitute a failure for tests on conditioned armour.

1.3.2.5 Coupons Sent to OLES

The Office of Law Enforcement Standards (OLES) a division within the National Institute for Science and Technology (NIST) had an interest in this test series in keeping with its research objectives of understanding the aging behaviour of body armour materials. As part of a parallel Biokinetics project sponsored by the CPRC, a protocol to determine a suitable replacement interval for body armour was being developed, also being of interest to the OLES. In keeping with the spirit of cooperation for the greater good of policing in both Canada and the United States, and with the agreement of the CPRC, key scientists at the OLES made themselves available for consultation. In return, we have made available to the OLES samples of the ballistic fabrics from the tested panels.

The OLES plans to conduct analysis of the fibre properties from the aged armour panels, and use our ballistic test results data in reference to their findings. To this end, we sliced the bottom 50 mm from each front panel tested, labelled and bagged them and shipped them to the OLES for their analysis [5].

1.3.2.6 Test Results

As mentioned earlier, testing was done in Phase I predominantly at fair speed and above. For Phases II and III we attempted to achieve a speed of approximately 426 m/s, such that normal scatter resulted in speeds below the fair speed range and within the fair speed range.

A results summary is provided for the 150 front panels from Phase I testing, the 150 panels from Phase II testing, and the 150 panels from Phase III with all the data combined (Table 2). Note under *Perforations* that total counts all perforations (including multiples) whereas *Panels* counts each panel that suffered one or more complete perforations. A single panel might be tabulated multiple times if there were perforations in different speed categories. Back face signature (BFS) was measured for all fair speed shots where there was no perforation.

Table 2: Summary of all Phases combined (450 panels).

Standard (level II)	Qty Panels	.357 speed	Qty Shots	Perforations		BFS>44mm	
				Total	Panels	Total	Panels
NIJ 0101.03	356	below fair (<425m/s)	626	19	16		
		fair (425-440m/s)	1050	58	49	303	184
		above fair (>440m/s)	203	82	78		
NIJ 0101.04 and NIJ (2005)	94	below fair (<427m/s)	259	5	4		
		fair (427-445m/s)	262	8	7	39	29
		above fair (>445m/s)	15	7	7		

The overspeed results (above fair), in Phases II and III had only one panel that suffered a perforation compared with 84 panels in Phase I. This is of course to be expected since we did not attempt to shoot above the fair range in Phases II and III.

Simply comparing the numbers of perforations and/or panels perforated among the various phases could be misleading because of the different numbers of shots taken. In the Phase I data, there were a total of 615 shots, compared with 900 shots in each of Phases II and III. The fewer shots in Phase I was because there were two 9 mm shots taken per panel (that were not found to be a significant threat for perforation). Calculating the perforation rate by dividing the quantity of perforations by the quantity of shots taken, the results are shown in Table 3. These rates combine the totals from NIJ-0101.03 and NIJ-0101.04 panels. Note that these rates include multiple perforations on a single panel.

Table 3: Panel perforation rate (qty. perfs. divided by qty. shots taken).

	Phase I	Phase II	Phase III	Overall
Below fair speed	4.4%	1.7%	3.2%	2.7%
Fair speed	6.1%	3.0%	6.6%	5.0%

Overall, 5% of fair shots were found to perforate an armour panel. But from a police safety perspective, the overall below fair perforation rate of 2.7% attracts more attention. It suggests that roughly three shots in one hundred will perforate below the minimum requirements of the standards. While this may indeed be the case, it does not tell the whole story and it is important to consider the actual speeds at which these perforations occurred.

In our testing, 2415 shots were fired. The lowest perforation speed of NIJ-0101.03 armour occurred twice at 417 m/s. The lowest perforation speed of NIJ-0101.04 armour was a single event at 416 m/s. To put this speed into context, this brief review of armour ballistic standards is offered.

All of the armour tested was produced to meet standards developed by the Office of Law Enforcement Standards and issued by the National Institute of Justice (NIJ) as NIJ-0101. Various versions of this standard have been issued over the years, beginning with NIJ-0101.00 in 1972. Later versions NIJ-0101.03 and NIJ-0101.04 were introduced in April 1987 and September 2000 respectively, progressing through to the current version NIJ-0101.06 which was issued in July 2008. An interim NIJ 2005 standard is also referenced, which was a re-certification status of NIJ-0101.04 compliant armour. All of the armour tested was, when new, certified to be in compliance with the NIJ-0101.03 and NIJ-0101.04 versions of the standard.

At each revision of the standard a number of changes were made to reflect the additional knowledge which was gained in the subject area in the intervening years. One of the most notable additions to the NIJ-0101.06 version was the concept of differing performance requirements for new and “conditioned” armour. The latter samples are conditioned by being tumbled for ten days in a controlled heat and humidity environment, as the standard says “…to subject test armors to conditions that are intended to provide some indication of the armor’s ability to maintain ballistic performance after being exposed to conditions of heat, moisture, and mechanical wear.” New armour is tested with bullet speeds which are elevated above expected street speeds. Armour which has been through the conditioning protocol is tested with reduced bullet speeds – less than the new armour but still greater than expected street speeds. These conditioned armour test speeds and approximate street speed are illustrated in Figure 1. No previous version of the standard included such a performance requirement for conditioned armour.

During the testing of these 450 armour samples, which was carried out in accordance with the NIJ-0101.03 and NIJ-0101.04 standards, we experienced some .357 shots which perforated the armour at bullet speeds below that which should have been stopped by the armour when new. However, all but three of these perforations were at speeds higher than the minimum required performance for conditioned armour in the NIJ-0101.06 version of the standard.

Since there was no change for the new armour test speed for this threat from the NIJ-0101.04 to the NIJ-0101.06 version of the standard, it seems reasonable to review the test results of aged NIJ-0101.03 and NIJ-0101.04 compliant armour in comparison to the reduced performance level permitted for conditioned armour incorporated into the NIJ-0101.06 standard.

In our testing, there were 220 shots taken whose speeds fell within the fair range for conditioned armour (399-417 m/s), of which only three perforated, for a conditioned perforation rate of 1.4%.

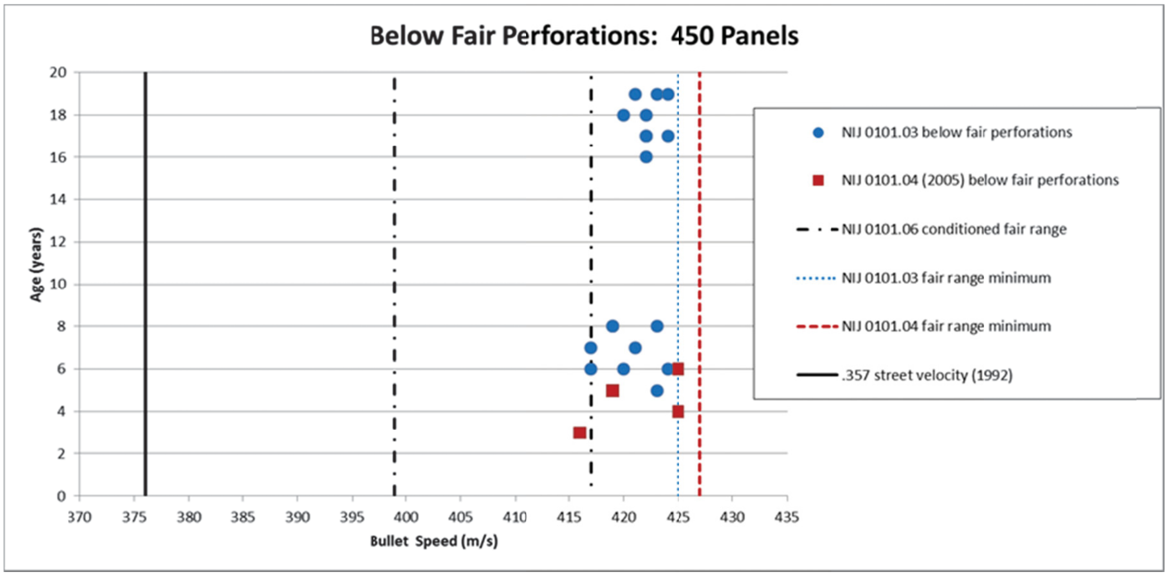


Figure 1: Below fair perforations (450 panels).

1.3.2.7 Velocity Distribution

As discussed previously, in Phase I testing the intent was bullet speeds within the fair range and also overspeed. In Phases II and III the intent was to focus on the low end of the fair range, as a clear indicator of aged armour performance from the user's perspective. The number of shots fired per bullet speed is illustrated in Figure 2 for all Phases combined. The mean Phase II and Phase III velocity was 425.9 m/s, which is very close to the attempted bullet speed of 426 m/s for all panels. There are approximately 50% more .357 shots in Phase II and III compared with Phase I because there were two 9 mm shots per panel during Phase I, which are not discussed here.

Figure 2 clearly shows the large number of shots intentionally taken below the fair range, which is the region of most specific interest to police.

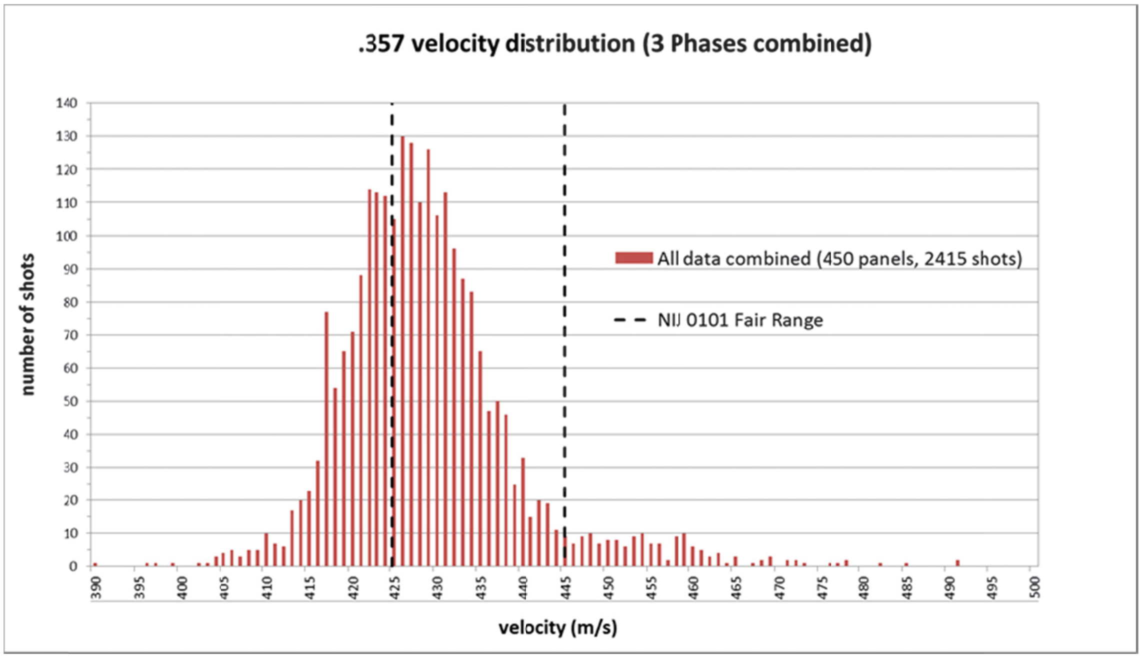


Figure 2: Velocity distribution for all Phases combined.

1.3.2.8 Perforation Risk vs. Projectile Velocity

The overall data sets of .357 shots from Phases I, II and III are illustrated below combined and shown in Figure 3. The figure illustrates perforations as data points at the 100% line, and stops as data points on the 0% line. In Phase I testing there were shots at elevated speeds (called overspeed). Data points from shots that were inadvertently too slow or too fast are included here also.

Dichotomous data (either perforation or stop) with a general overlap as seen here can be generalized using binomial logistic regression. This generates a probability function to relate the risk of perforation to the .357 projectile's speed. The equation takes the form of:

$$p(x) = (1+exp(-B_0-B_1x))^{-1}$$

This is used to generate the logist risk curve and 95% confidence curves in Figure 3.

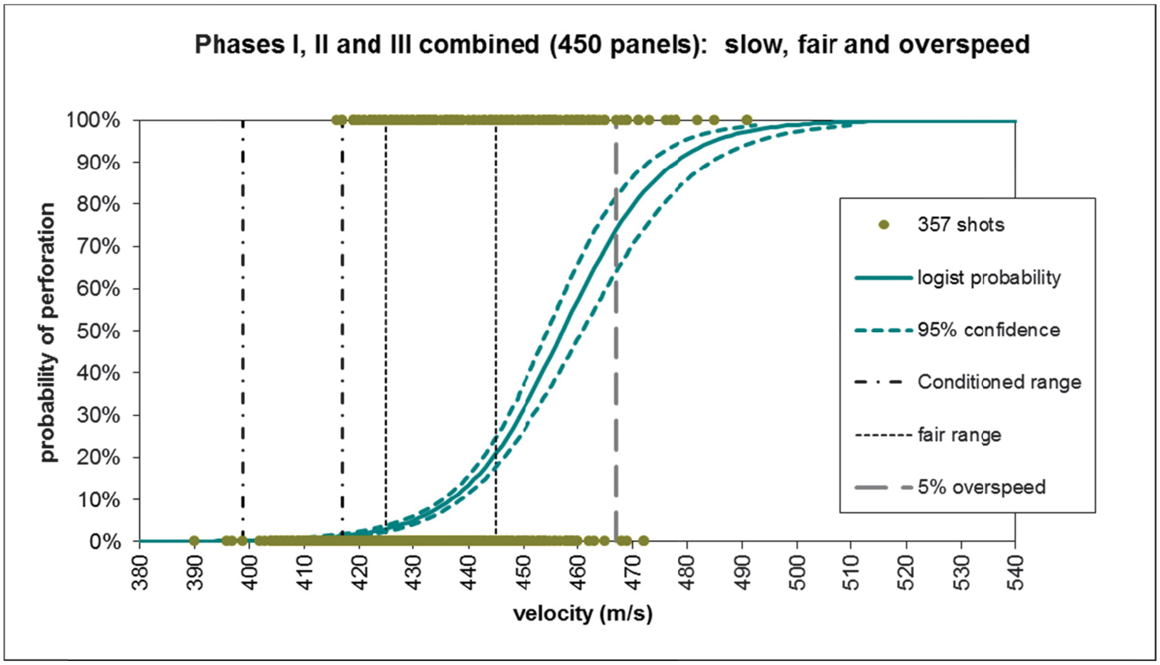


Figure 3: Phase I, II and III combined: probability of .357 perforation.

It is interesting to note that at 417 m/s (the upper end of the NIJ-0101.06 conditioned armour fair speed range) the logist model predicts a perforation risk of 1.3%, which compares well with our actual data conditioned perforation rate of 1.4%.

It is now known that even after concentrating a much higher number of bullets in the sensitive zone between the NIJ-0101.06 fair range for conditioned armour and the NIJ-0101.03 and NIJ-0101.04 fair ranges for new armour, the aged armour samples supplied by police services appear, by and large, to perform as required by the new standard for conditioned armour.

Nevertheless, the reader is reminded that all samples were donated for this testing, not specifically selected as a random and statistically significant sample from the police population. This was armour already decommissioned from service and slated for disposal. We have no way of knowing how this tested armour relates to the population of armour currently being worn in active service.

1.3.2.9 Perforation Risk vs. Age of Armour

The armour tested in the three Phases for .357 bullets ranged from 1 to 19 years old. The age was calculated from the date of manufacture to the date of testing. The age number is presented similar to a person's age, not rounded up or down to the nearest whole number.

The data from all Phases combined is shown in Figure 4. Perforation data is also included, showing the combined panels that perforated at fair velocity and below as well as the below fair count only. Fair velocity and below perforations occurred in panels of all ages from 3-19 years, the majority of which were in 5-8 year old armour and 18 year old armour. However, it is the below fair count that is of the highest interest here. Below fair perforations occurred in panels from 3-8 years old and from 16-19 years old.

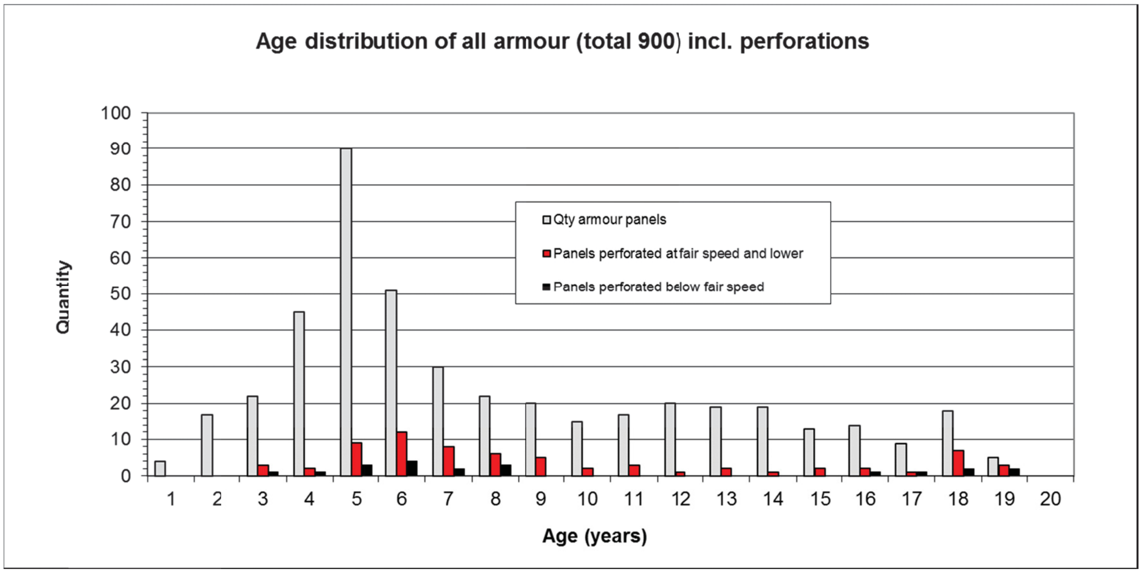


Figure 4: All Phases combined age distribution with fair velocity and lower perforations and below fair perforations only.

The count of perforations by age is not meaningful without reference to the number of panels involved. In Figure 5 the rate of panel perforation is provided, where the quantity of panels of each age is divided by the number of panels that suffered one or more perforations. Overall below fair perforation rates were highest for armours 19 year old (40%) and 8 years old (14%).

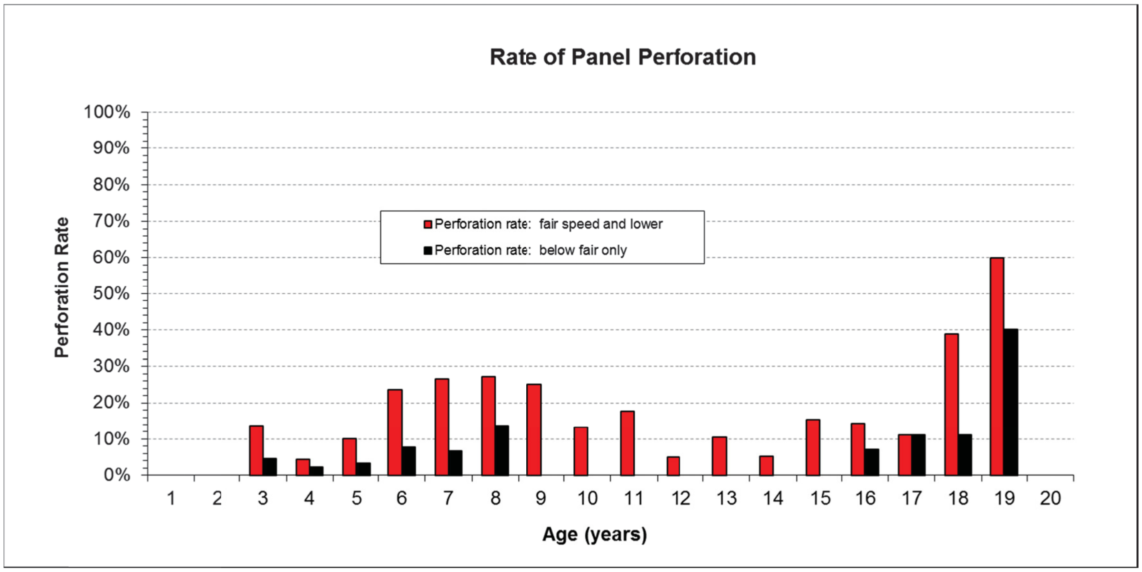


Figure 5 : Overall perforation rate for fair velocity and lower and below fair only.

There does not appear to be a clear relationship between the age of the armour and its performance in relation to .357 magnum bullets. This observation was noted for each Phase individually as well as overall. While there does appear to be a fall-off in bullet resistance at 16 years and older, the rate of panels perforated below fair speed among 6-8 year old armour is remarkably similar to the 16-18 year old armour. Further, the three instances of panels allowing perforations at the top end of the NIJ-0101.06 conditioned armour performance range (416 m/s, 417 m/s and 417 m/s) occurred in samples aged 3, 6 and 7 years. Clearly factors beyond simply aging are likely involved.

1.3.2.10 Shot Sequence

The testing reported herein included six or more shots per panel. There was concern that multiple preceding shots might have compromised the bullet resistance when the later shots were taken. The shot number associated with perforations at fair speed and lower is provided below in Figure 6. The first shot is most frequently associated with perforation (24%) followed by the fourth shot (20%). The sixth shot was associated with only 6% of perforations. Perforations at the seventh and eighth shots were infrequent and only in Phase I, but were very low percentages also. These data suggest that the shot sequence was not a relevant factor.

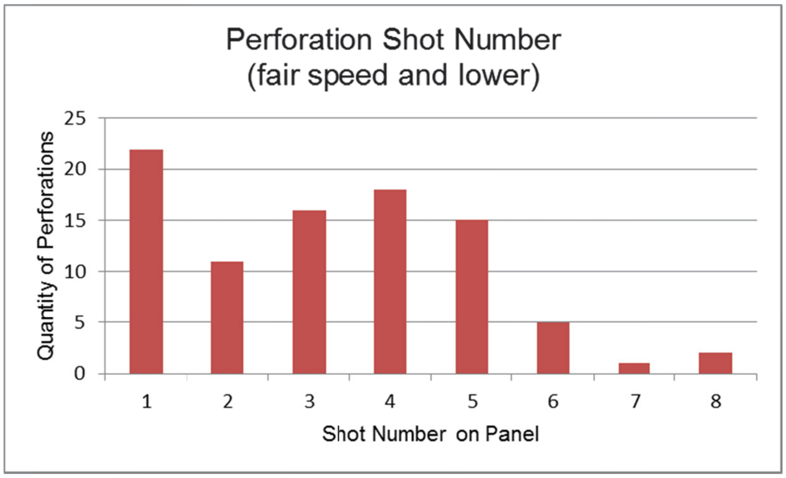


Figure 6 : Shot number associated with perforations at fair speed and lower.

1.3.2.11 Influence of Armour Size on Perforation

Not all sizes of armour must be submitted for certification. For example in 0101.03 only one size was required to pass testing as long as all further sizes were made of the same materials and layer count. Small sized armour would typically not be tested because the shot spacing would be closer making it more difficult to pass a 6-shot test sequence. While this is not necessarily a cause for alarm, given the low likelihood of a vest in service sustaining multiple shots, it did seem worth checking on the size range of the armours that sustained perforations.

Perforations at fair velocity or below occurred in front panels sized from 34 to 52 inches with a mean of 44.06 inches and standard deviation of 3.67 inches. There was no apparent correlation of perforation with size.

1.3.2.12 P-BFS General Summary and Conclusions

The following observations and conclusions are summarized at the completion of three Phases of P-BFS testing of front panels of aged body armour:

1. For the 450 panels tested, 2415 shots were fired. Among them 1312 shots were fired within the fair velocity range of certification testing and 56 panels (12% of the total number of panels) failed in .357 perforation. There were 885 shots fired below fair

velocity and 20 panels (4% of the total) failed to defeat the projectile below the stated minimum speed of protection. These armours were certified to the NIJ-0101.03 and NIJ-0101.04 standards. But if these results are reviewed within the context of the new NIJ-0101.06 standard which allows a margin for decreased performance for conditioned armour, only three of these perforations in naturally conditioned armour (1.4% of the total) would be considered failures.

2. The bullet speed range for conditioned armour as described in the newest NIJ-0101.06 standard is 399-417 m/s. Three panels allowed perforations at speeds within this range, one at 416 m/s and two at 417m/s. These panels were aged 3, 6 and 7 years respectively.

3. Perforations at fair speed or lower were experienced in armour at all ages from 3 to 19 years old.

4. The highest overall panel perforation rates for fair speed and lower were among 19 year (60%), 18 year (39%) and 8 year (27%) old armours respectively. The highest overall panel perforation rates for below fair only speeds were among 19 year (40%), 8 year (14%) and 17-18 year (11%) old armours respectively

5. Of the 450 panels tested, 213 panels (47%) exceeded the minimum back face signature of 44mm at fair velocity. This may be expected as armour stiffness is reduced after prolonged wear and is not a criterion for failure in conditioned armour under NIJ-0101.06 testing.

6. The overall logist model for the combined data sets predicted a perforation risk of 1.3% at 417 m/s, which compared well with the actual conditioned perforation rate of 1.4% within the NIJ-0101.06 conditioned fair range.

7. Based on the particular makes, models and ages in this test series there is no clear trend to suggest that bullet resistance necessarily decreases predictably with age. However, a high perforation rate was noted among the small sample of panels 16 years and older.

8. The large number of NIJ-0101.03 armour samples less than 10 years old suggests that some police forces continued to purchase armour to this outdated standard, despite it having been superseded by the NIJ 0101.04 standard.

9. The armour samples tested in this report were not specifically selected as representative samples of armour in continued use by police services. This was armour already decommissioned and slated for disposal. We have no way of knowing how this tested armour relates to the population of armour currently being worn in active service.

1.3.3 V50 Testing on Minicel® and Clay Backing

1.3.3.1 6-Shot V50 Tests on 120 Back Panels from Phase I Armour

As just discussed, in the Phase I testing there were many panels that allowed perforations by .357 bullets within the fair velocity range. Nevertheless, the majority of shots were indeed stops. Binary logistic regression favours a more balanced number of perforations and stops, so to improve statistical confidence in the Phase I data, another test series was proposed in which those back panels that were mated to front panels from Phase I would also be shot. Not all of the Phase I panels had matching backs, and after careful comparison, only 120 matching rear panels were available.

These matched back panels were tested in a V50 methodology, sometimes called a ballistic limit (BL) test, whereby a series of shots at converging speeds that produce both perforations and stops is used to establish an estimated speed at which a panel will stop a bullet 50% of the time. The V50 was determined using the methodology defined by MIL STD 662F 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. These 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. The remaining shots that were not eligible for V50 calculation, if any, remained valid as data points in calculating logist perforation risk functions.

Ballistic tests are performed upon a deformable surface representing the structure of the human body beneath. In NIJ certification testing of new armour, a calibrated Plastilina clay backing material is used. In cases where perforations are not expected (e.g. certification tests), the clay is dented but otherwise not contaminated by a test. In V50 testing, where perforations are mandatory, it is burdensome and costly to decontaminate and repair the clay backing surface after each test.

The Technical Purchase Description for Bullet Resistant Plates (hard armour inserts) for the Canadian Forces recommends the use of Minicel® foam backing for V50 testing[16][8]. Minicel® is not affected over a large area by each perforation in the same way as clay and may be re-used for multiple test samples. As a consequence, testing with this backing is more cost effective. Minicel® has also been shown to compare favourably in V50 testing with traditional Plastilina clay in limited testing[1] .

In order to maximize the number of samples which could be tested within the program budget, and in consultation with DRDC Valcartier, Minicel® foam backing was used for this V50 test program on soft body armour. All tests were at ambient temperatures and in dry conditions. All shots were straight on. The quantities of panels tested per NIJ standard are provided in Table 4.

Table 4: 120 back panels Type II certification standards.

Standard	Quantity
NIJ 0101.03	106
NIJ 0101.04	10
NIJ (2005)	4

The overall age range of the 120 samples was from 4 to 19 years; mean 8.6 yrs; standard deviation 3.0 yrs. The age distribution is provided below in Figure 7. The majority of samples ranged from 6 to 8 years old.

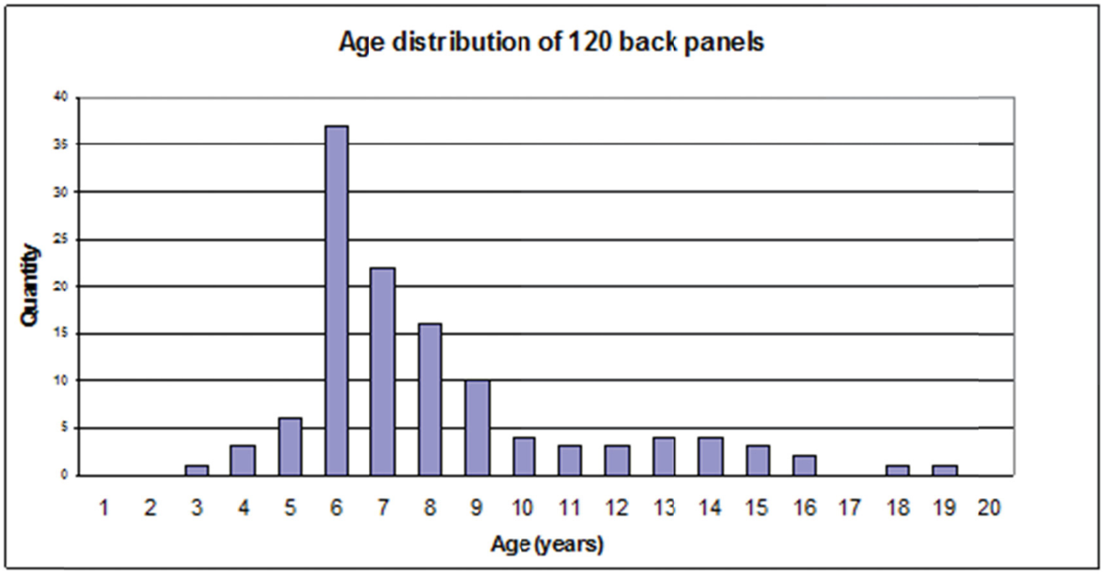


Figure 7: Age distribution of 120 back panels.

The V50 was calculated as the arithmetic mean of six shots, including three stops and three perforations, within a 45 m/s window. The calculated V50 for the 120 panels ranged from 449.2 m/s to 528.8 m/s; mean 479.1 m/s; standard deviation 13.6 m/s. The distribution of individual V50 calculations is shown in Figure 8.

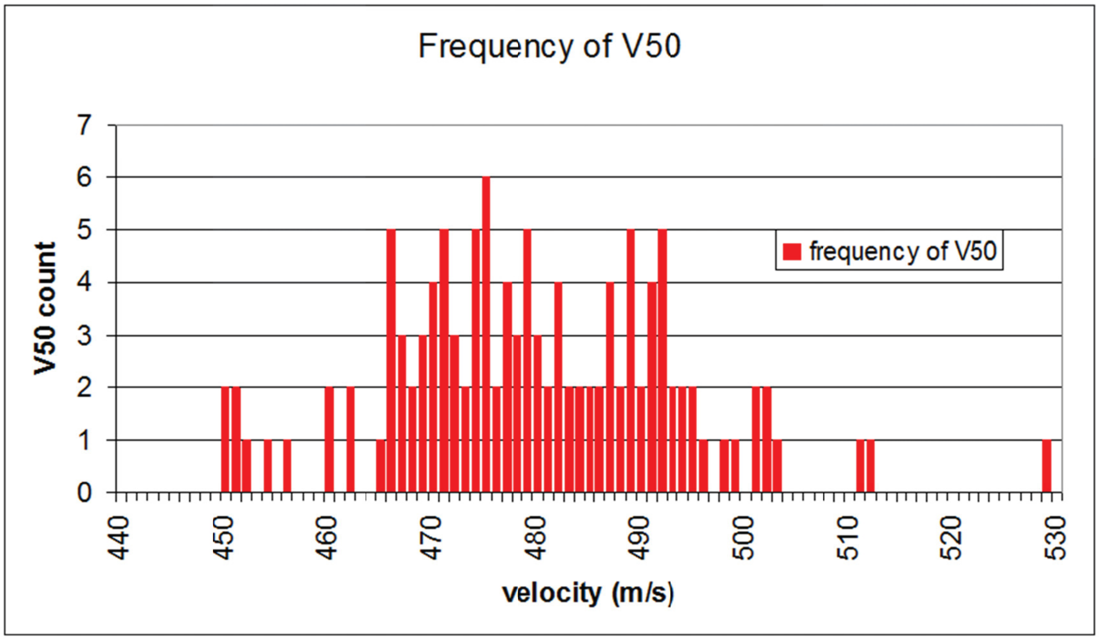


Figure 8: V50 distribution of 120 panels.

To investigate whether or not the V50 of the individual panels was affected by age, a correlation plot is provided in Figure 9. A linear regression line through the data suggests that V50 actually increases marginally with age (less than 1% over 20 years), but the very low correlation coefficient ($R^2 = 0.0025$) suggests that this unlikely scenario is an anomaly caused by the spread of data. As with the previous Vproof tests, the results indicate no correlation of armour ballistic performance with age.

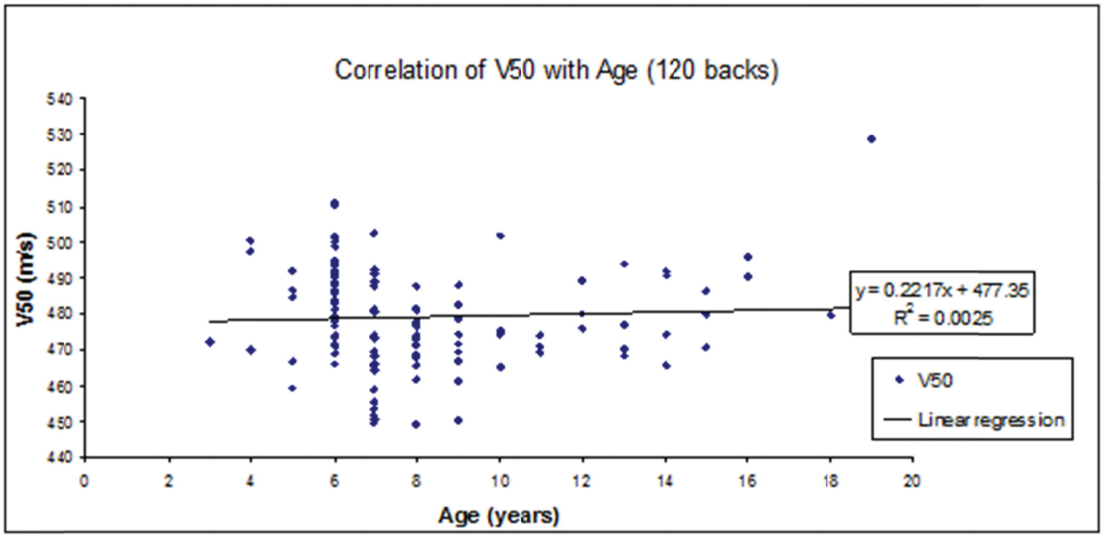


Figure 9: Correlation of V50 by age (120 backs).

The overall data set of .357 shots from the V50 testing is illustrated in Figure 10. Perforations are shown as data points at the 100% line, and stops as data points on the 0% line. Extra data points from shots that were inadvertently too slow or too fast are included here also.

The logist curve predicts a 50% risk of perforation at 476.3 m/s, which is similar to the mean V50 of 479.1 m/s determined above.

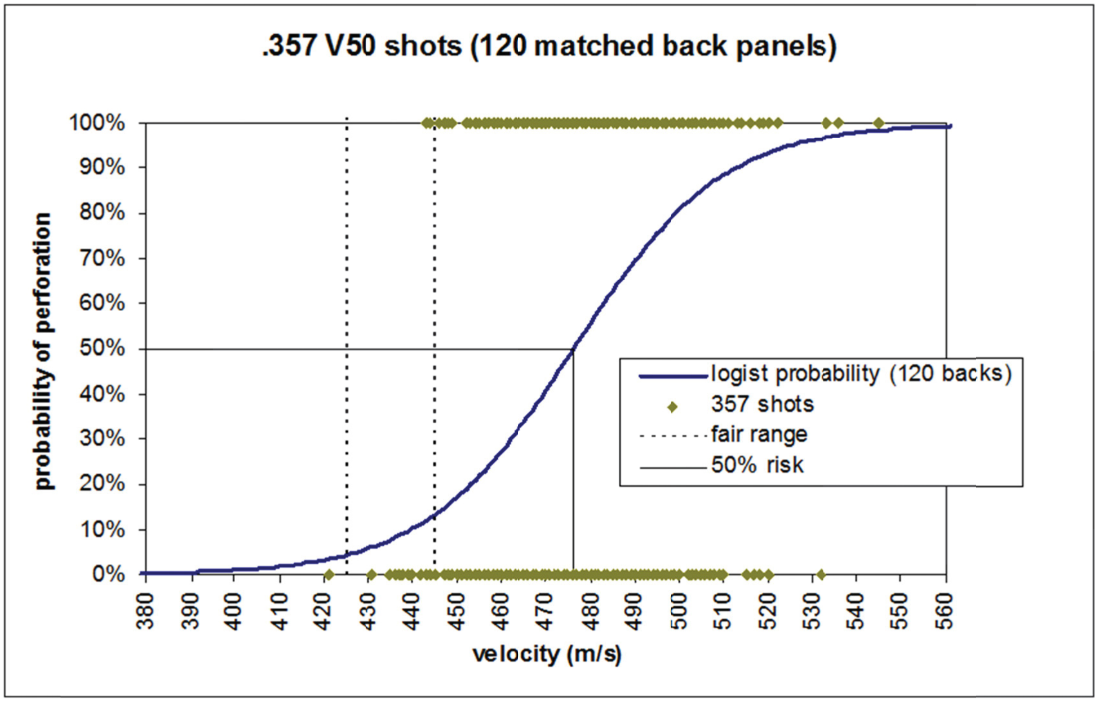


Figure 10: Probability of .357 perforation vs. velocity (120 back panels).

The main objective of this V50 program was to improve the confidence in the Phase I front panel test data by supplementing it with back panel test data. Since these two data sets are not unique, their logist perforation risk curves for .357 projectiles should be similar to each other. To check this, the logist curve for only the matching 120 front panels (.357 data only) is shown in Figure 11. Included in the figure is the logist curve for all 150 front panels for comparison.

Two things are immediately apparent. First, the deletion of 30 panels from the Phase I dataset has minimal effect on the resulting logist curve. The constant and step variables are almost identical to each other, and the two curves are only 4.7 m/s apart at the 50% risk level. Second, the logist risk curves for the 120 front and 120 back panels (Figure 10 compared with Figure 11) are remarkably *dissimilar*. Yet these are panels matched in production, assumed to be equal.

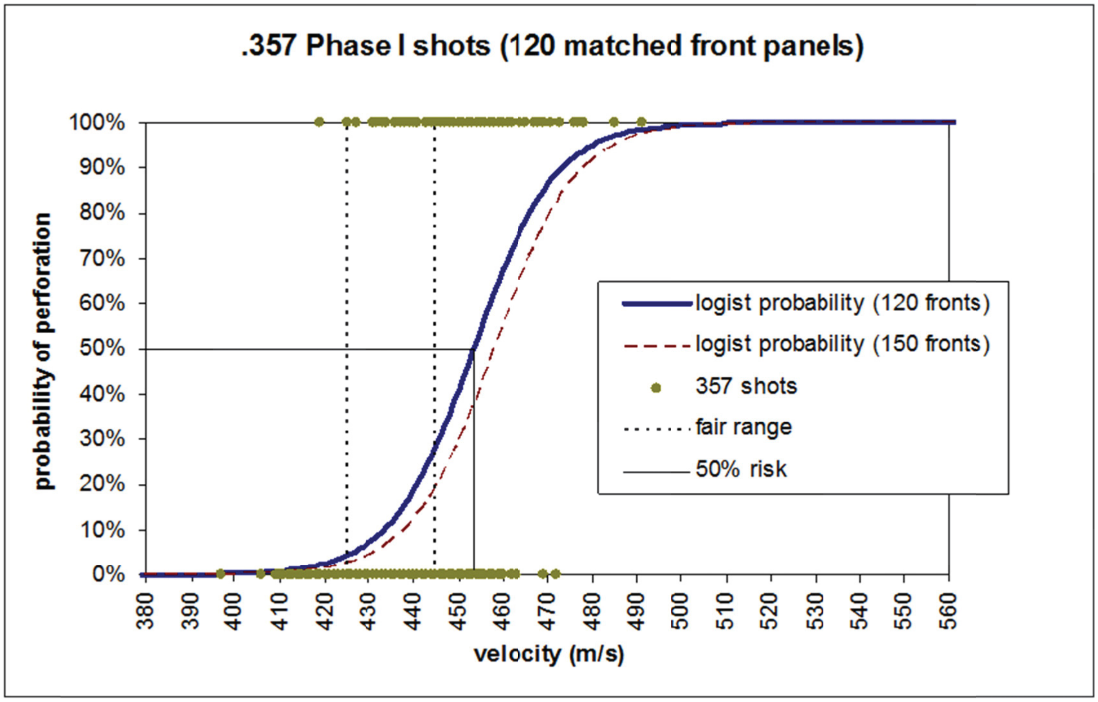


Figure 11: Prob. of .357 perforation vs. velocity (matching 120 front panels from Phase I).

Further observation of these two figures reveals that the ranges of perforation and stop velocities are very different also. This is illustrated more clearly in Table 5 below. The fastest speed of a defeated bullet was 60 m/s higher for the back panels than the fronts and the overall mean of stops was 36.4 m/s higher. Comparatively, the slowest speed of perforation was 24 m/s higher for the backs and the overall mean of perforations was 37.7 m/s higher. At the 50% logist risk of perforation, the back panels predicted a velocity 22.9 m/s higher than the matching front panels.

Table 5 : Projectile velocity extrema for 120 matching front and back panels.

Perforation		Velocity (m/s)		
		back 120	front 120	*diff.*
no	max	532	472	60
	min	421	397	24
	mean	470.3	433.9	36.4
yes	max	545	491	54
	min	443	419	24
	mean	488.5	450.8	37.7
50% logist		476.3	453.3	22.9

These data suggest that the V50 of the back panels is higher than the front panels. This is counter-intuitive: they should be the same. The remarkably different character of the back and front panels suggests their data should not be mixed together. Possible reasons include:

Mechanical Wear: We have assumed that the front and back panels provide equal levels of ballistic protection. This assumption holds for new armour, but may be invalid for aged armour. As worn in normal service, it is conceivable that the front panel suffers more mechanical wear due to folding and bending each time the officer sits and stands. Automotive seat belts and the officer's heavily laden duty belt could compound this.

Construction: To investigate whether or not matching front and back panels were constructed differently, several shot packs from the V50 tests were opened and the layer count was compared with that of the Phase I data. As expected, the front and back panels were made of the same materials and had the same number of layers.

P-BFS vs. V50 Shot Patterns: In the Phase I P-BFS testing, two projectiles were used, a 9 mm FMJ 8.0 g (124 gr) and a .357 magnum JSP 10.2 g (158 gr). The first three shots were .357s fired in the NIJ triangle pattern, one at each corner, and the fourth along one of the upper triangle arms. The remaining two 9 mm shots were within the triangle. In the V50 testing, a similar initial pattern of three .357s was done, one at each corner. The remaining three .357s were within the triangle. Both methodologies maintain a consistent distance from the edge of the shot pack and a minimum shot spacing, all following accepted protocols. We tried to keep the V50 shots spaced well apart from each other. It is known that multiple shots along the same weaving lines of ballistic fabrics might increase stress on a grouping of fibre strands. However, it was not possible to correlate the shot sequence with ballistic performance because of the velocity scatter involved.

Mincel® vs. Clay: Traditional ballistic testing on Type II soft body armour is done using a calibrated clay backing material. The Phase I front panel testing was done by this method. Despite Minicel® being used elsewhere for similar testing, it is the most likely cause of these observations.

To investigate this further, a dedicated testing program was undertaken comparing similar aged armour samples tested against clay and Minicel®, as described next.

1.3.3.2 10-shot V50 Tests of 25 Panels on Minicel® and 25 Panels on Clay

In the overall P-BFS aged armour programmes Phases I, II and III, a total of four hundred and fifty (450) sets of used soft body armour were donated by Canadian police forces. The three Phases of P-BFS testing only consumed the front panels. The rear panels from the Phase I armour were used for the above V50 testing on Mincel®. This left us with three-hundred (300) back panels from the Phase II and III series available for this Minicel® vs. clay investigation. The objective was to select from this group a subset of fifty panels that was as homogenous as possible.

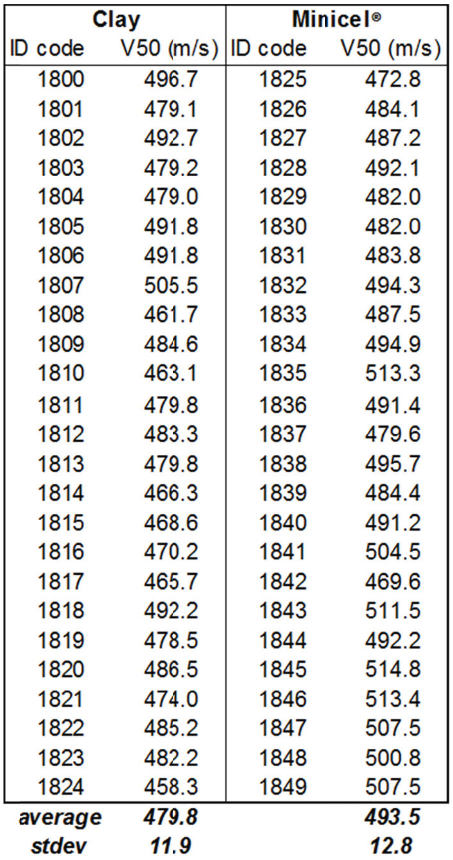
The hierarchy of selection criteria was: NIJ standard, manufacturer, model, size, age and police force. Note that all panels were NIJ-level II, so that was not a factor. NIJ 2005 was most desirable because the panels would be relatively new and certified to a more stringent protocol than previous versions. We were fortunate to find fifty panels all certified to NIJ 2005, all made by the same manufacturer and of the same model. Forty-nine were from a single police force.

The fifty panels were then sorted into subsets by year of manufacture. Each subset was divided into clay and Minicel® stacks balanced by size as equally as possible. Note that garment length was not a sort criterion. Then the clay and Minicel® stacks were combined and their overall age and size average and standard deviations compared. Minor adjustments were made to balance the averages and minimize the standard deviations. The mean size for the clay group was 43.5 inches (sd 3.4 in.) and for the Minicel® group was 43.8 inches (sd 4.3 in.). The mean age for the clay group was 52.3 months (sd 12.0 mo.) and for the Minicel® group was 54.3 months (sd 11.4 mo.).

In the previous V50 program, there was concern that there would not be sufficient space for more than six shots per panel, but after further review it was deemed feasible to maximize the test area and conduct ten shots. The V50 was calculated using the arithmetic mean based on ten shots comprising an equal number of “highest partial” and “lowest complete” perforation impact velocities within a 40 m/s velocity spread. Note that in some cases up to sixteen shots were necessary to achieve this criterion. The remaining shots that were not eligible for V50 calculation, if any, remained valid as data points in calculating logist perforation risk functions. All tests were at ambient temperatures and in dry conditions. All shots were straight on.

The individual V50 scores are shown in Table 6. The mean V50 calculated for clay was 479.8 m/s (sd 11.9 m/s) and for Minicel® it was 493.5 m/s (sd 12.8 m/s), higher by 13.7 m/s. A two-tailed t-test was performed on the means of these two groups. The difference was found to be significant at the 5% level (p=0.00028).

Table 6: Arithmetic V50 tabulation.



Clay		Minicel®	
ID code	V50 (m/s)	ID code	V50 (m/s)
1800	496.7	1825	472.8
1801	479.1	1826	484.1
1802	492.7	1827	487.2
1803	479.2	1828	492.1
1804	479.0	1829	482.0
1805	491.8	1830	482.0
1806	491.8	1831	483.8
1807	505.5	1832	494.3
1808	461.7	1833	487.5
1809	484.6	1834	494.9
1810	463.1	1835	513.3
1811	479.8	1836	491.4
1812	483.3	1837	479.6
1813	479.8	1838	495.7
1814	466.3	1839	484.4
1815	468.6	1840	491.2
1816	470.2	1841	504.5
1817	465.7	1842	469.6
1818	492.2	1843	511.5
1819	478.5	1844	492.2
1820	486.5	1845	514.8
1821	474.0	1846	513.4
1822	485.2	1847	507.5
1823	482.2	1848	500.8
1824	458.3	1849	507.5
average	***479.8***		***493.5***
stdev	***11.9***		***12.8***

Using only the ten shots per panel that were used for individual V50 calculations (and ignoring the extra shots taken), the logist curves for the clay and Minicel® are shown in Figure 12. For the clay logist model, V50clay = 479.9 m/s. For the Minicel® logist model, V50minicell = 493.5 m/s. The difference is 13.7 m/s higher for the Minicel®. At the 50% risk level, the 95% confidence bounds just touch each other, without overlapping. The fact we have non-linked intervals confirms that the data sets are uniquely different from each other at their V50 levels.

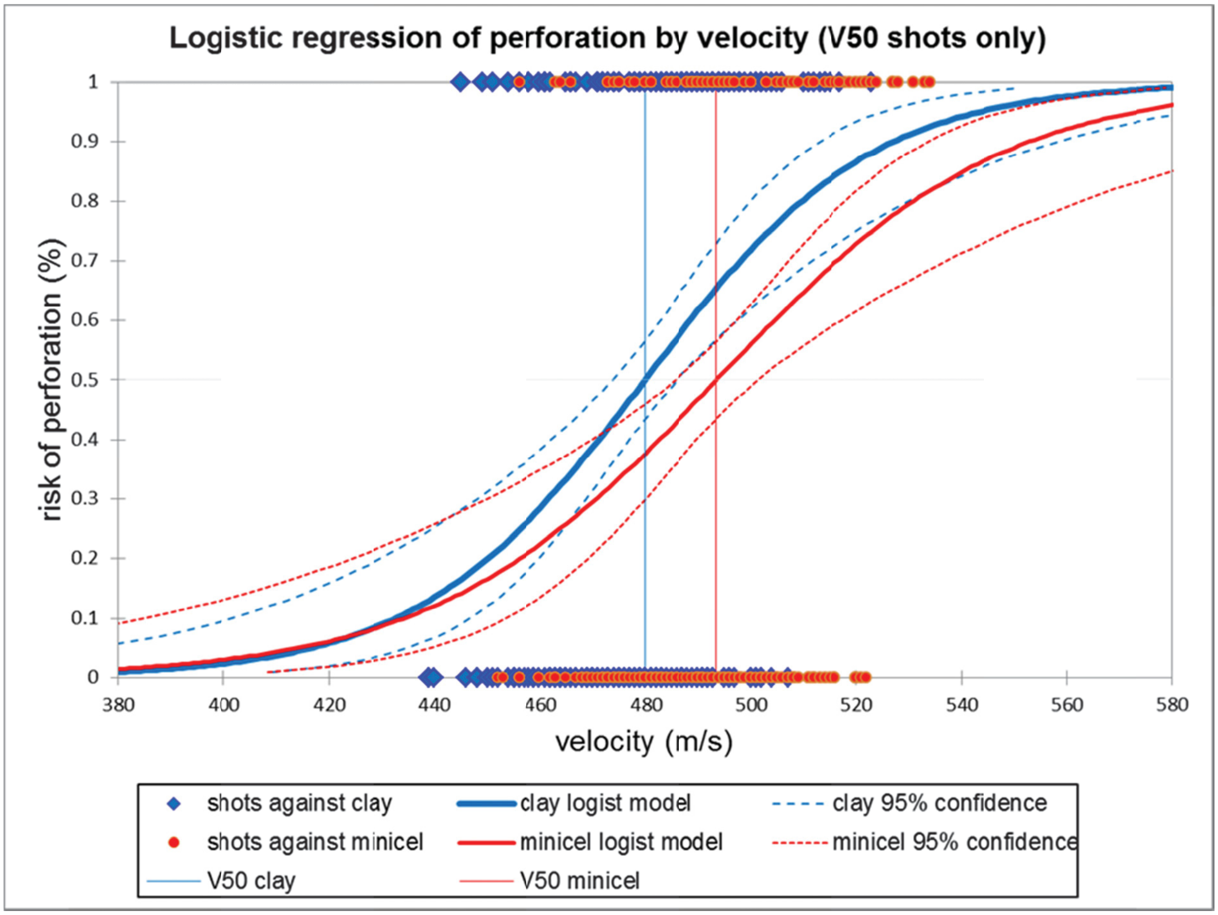


Figure 12: Logistic regression perforation vs. velocity (V50 shots only).

Using all the shots taken for all panels, not only those used for individual V50 calculations, the logist curves for the clay and Minicel® are shown in Figure 13. On clay there were 140 perforations and 156 stops. For the clay logist model, $V50_{clay}$ = 480.4 m/s. On Minicel® there were 140 perforations and 142 stops. For the Minicel® logist model, $V50_{minicell}$ = 494.2 m/s. The difference is 13.8 m/s higher for the Minicel®.

At the 50% risk level, the 95% confidence bounds do not overlap, confirming again that the data sets are uniquely different from each other at their V50 levels.

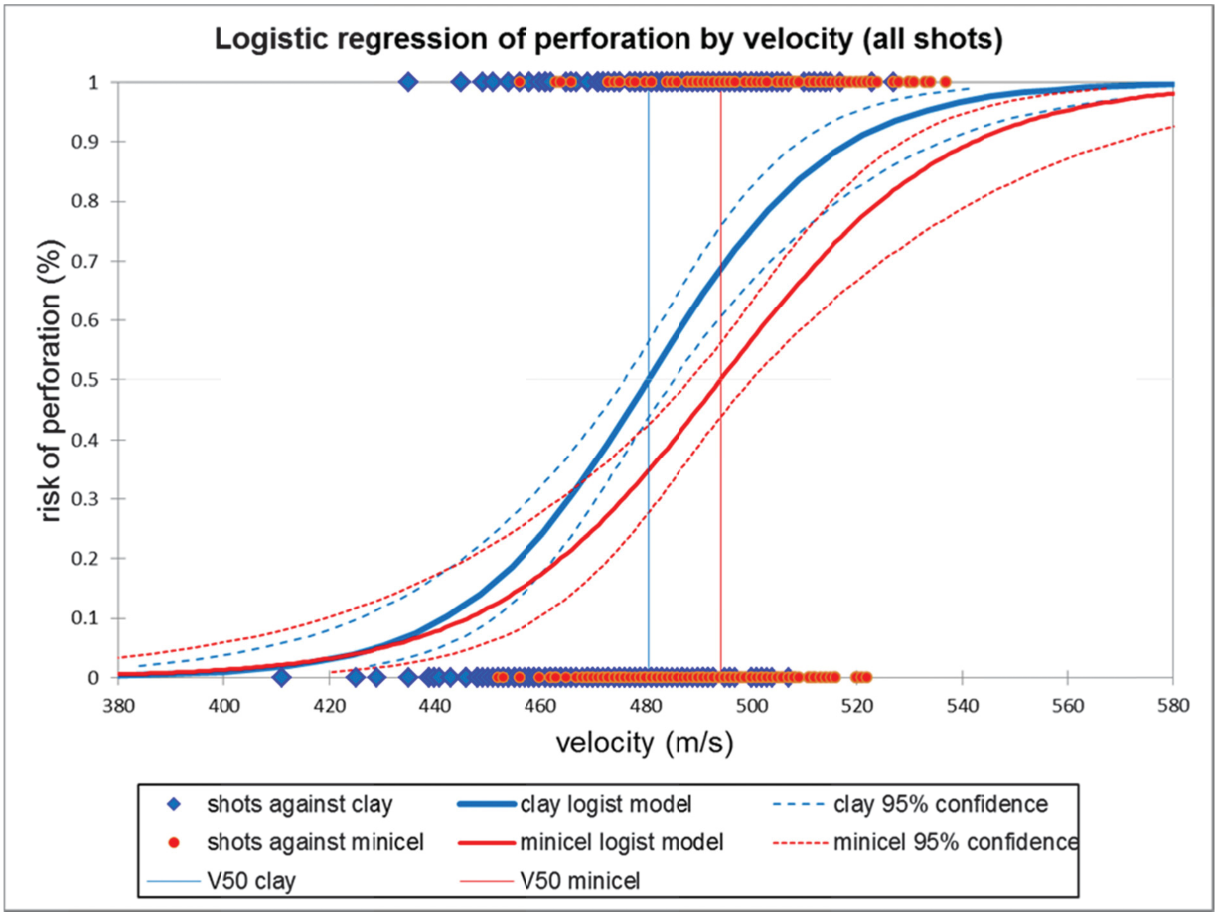


Figure 13: Logistic regression perforation vs. velocity (all shots).

The backing material used for ballistic testing has been a subject of considerable debate. The original version of the NIJ ballistic standard, NIJ-0101.00 (1972) used air as the backing material for perforation tests and "a block of non-hardening modeling clay" as the backing for deformation tests. The use of air as a backing material was later dropped citing the lack of evidence relating air-backed test results to the projectile-fabric interaction on a torso, human or otherwise.

The specific suggestion of Roma Plastilina clay was first introduced in NIJ-0101.01 (1978) as a non-resilient backing material for testing both deformation and penetration. Like the more current NIJ standards, it noted that Roma Plastilina No. 1 modeling clay was "found to be suitable" as a backing material but did not require its use, although it did specify a drop test to be performed to check the consistency of the backing material.

It is readily intuitive that attachment to a firm backing will make the vest more penetrable than no backing at all. Attachment to a backing influences penetration in two ways. Clay backing prevents bulk movement of the vest away from the shot, and it allows part of the vest to be pinched between the backing and the bullet, making for a realistic simulation event.

However, the clay is arguably harder than some parts of the human body, and a bullet may have a greater chance of penetrating the vest on a clay backing than it would on a human's ventral region. The human sternum, by contrast, is harder than the clay and may be less prone to penetration. This is confusing, because a variety of materials other than modeling clay are often used as backing in tests for other purposes than NIJ certification. Examples include 10-percent ballistic gelatin, 20-percent ballistic gelatin, rigid foamed polystyrene (Styrofoam), foamed polyurethane rubber, RTV silicone rubber, soap, plywood, human and animal cadavers, and live animals. Of these, only Styrofoam and soap are sufficiently inelastic for use for deformation measurement in an NIJ-like test.

The repeatability and reproducibility of oiled clay backing material has also been debated. In the NIJ-0101.03 and .04 standards, Roma Plastilina is not a mandated material, only a suggested material. Any material satisfying the NIJ calibration procedure, which includes several drops of a steel ball from fixed heights onto the clay surface, and achieving a particular depth of indentation, was considered acceptable for that certification testing[4]. Yet researchers have used other types of modeling clay as backing material and found that deformation is affected by choice of material. For example, researchers at the Home Office Scientific and Development Branch in England have calibrated deformation in Plastilina to deformations in Plasticize and PP2 as a function of bullet velocity. In these comparisons all three backings were conditioned so as to pass the drop test specified in NIJ-0101.03 yet different test results were observed.

Some materials are known to yield different results; others, not yet tested by NIJ or NIST, could differ more dramatically. Although clay composition has been demonstrated to affect the results of the deformation test (for protection from non-penetrating bullets), it is not certain that it affects the results of the penetration test. In fact, Anctil et al. demonstrated that Minicel® foam was a feasible substitute for calibrated clay in V50 tests using 9 mm bullets[1]. DRDC has also used Minicel® successfully in hard armour research testing[16].

Nevertheless, for our V50 testing of aged body armour certified to the NIJ 2005 Level II standard using .357 magnum bullets, there is indeed a difference between Minicel® and clay backing materials. Calculated by arithmetic mean of individual V50's, logistic regression of V50 shots only, or logistic regression of all shots, the V50 on Minicel® was nominally 14 m/s higher than on clay.

Efforts were made to ensure that the armour samples were as similar as possible. Ideally, new armour would have been purchased for this program, but budgetary constraints precluded that option. The panels used for this testing were all the same make and model and were relatively new although there was limited information available about their service history. Effort was made to ensure that the age and size distribution of panels tested on clay and Minicel® were as similar as possible.

In previous reporting (Biokinetics R11-07) several factors were suggested that might have influenced the observed V50 differences between the P-BFS front panel and the V50 rear panel tests. These included mechanical wear effects being different between front and rear panels, construction differences front to rear and testing methodology differences related to shot patterns in P-BFS versus V50. These factors were controlled in this current investigation by including only back panels of identical make, model and construction, and testing them by the same methods. For purposes of this analysis, we assume that the sample groups were of the same construction and materials, and that the different V50 results must therefore be due to the different backing materials.

These results imply that previous V50 testing data using 120 matching back panels from the Phase I P-BFS testing of 150 front panels should not be merged.

---

[4] The NIJ-0101.06 standard, under 4.2.5.3 now specifies Roma Plastilina No.1 “In the interest of inter-laboratory conformity…”

1.3.3.3 V50 Testing on Minicel® vs. Clay General Conclusions

The main conclusions drawn from these two V50 test programs, as pertaining to the development of an Aged Armour Purchase and Replacement Protocol are twofold. First, the apparent non-relationship between V50 and age implies that there is risk associated with using V50 as the metric for determining the remaining service life of armour. Granted, the V50 testing on the 120 back panels was done on Minicel®, which we have shown to be non-comparable with clay, but nevertheless there should have still been a relative degradation with time over the age range of the armour. This observation is of course tempered by the aged armour of the 120 back panels being of different makes and models, but nevertheless all of similar construction and certification.

The second general conclusion is that, going forward, all testing should be done using established calibrated clay backing materials.

1.3.4 V50 Testing of Aged, New and NIJ-0101.06 Conditioned Armour

The newest NIJ-0101.06 standard includes an environmental conditioning protocol to simulate the combined exposure to heat, humidity and mechanical stress typical of in-service use. This was a culmination of research into the degradation of Zylon® ballistic fabric following an investigation of the failure of this material in armour worn by an officer in 2006 [17]. This procedure involves tumbling the armour panels in an elevated heat and humidity environment for a fixed period of time. Experiments proved that this new pre-conditioning process degraded the performance of Zylon® to a similar level as field-returned samples as evidenced by fibre strength measurements and ballistic testing[12].

What is less well documented is the effect these pre-conditioning stresses have on amour made with more traditional PPTA (p-phenylene terephthalamide) materials such as Kevlar® and Twaron®. To investigate this a study was undertaken whereby a ballistic evaluation of naturally aged PPTA based soft body armour from a major Canadian police service was compared with similar armour subjected to the new NIJ-0101.06 environmental conditioning protocol. Field-returned armour of similar design, size and age was obtained from a single police service. New copies of that armour were then purchased, made by the same manufacturer and to the same specification. Some of this new armour was subjected to the NIJ-0101.06 environmental conditioning protocol, and some remained in new condition. Equal numbers of field aged, new and conditioned armour were V50 tested and their results compared.

The Royal Canadian Mounted Police (RCMP) is Canada's national police force, serving the entire country in various capacities. The RCMP is unique among Canadian police services in that they have their own specification for soft body armour. All other police services purchase armour certified to some level of the NIJ-0101 standard. The RCMP specification is described in G.S. 1045-177 (June 1, 2007) and combines details of the armour size, composition, manufacturing and performance requirements. The ballistic testing requirements are identical to NIJ-0101.03, except for a unique specification for the 9 mm bullet.

Because of its size, the RCMP purchases large quantities of body armour on a regular basis to its unique specification, and for several years these armours have been manufactured by the same manufacturer. Each batch of armour must demonstrate compliance with G.S. 1045-177 as a condition of acceptance. Furthermore, the RCMP conducts routine laboratory testing of in-service armour to verify its continued compliance. All armour that is submitted for sample testing or otherwise retired from service gets routed through the supply depot in Ottawa, ON.

This created a supply of aged body armour uniquely positioned for the research: all made to the same specification by the same manufacturer. Furthermore, batch sample testing at the point lot acceptance ensured a common minimum performance when originally put into service. Lastly, and most importantly, the same manufacturer was able to supply the identical product new.

The armour supplied by the RCMP was produced specifically to the G.S. 1045-177 specification, Level II. The armour was predominantly seven years old, but one panel was only 2 years old. The average age was 7.5 years (sd 0.7 years) Sizes ranged from 40-42R to 48-50T inches. The average size was 43.7-45.7 inches. Only back panels were tested.

One hundred new armour panels were ordered from the same manufacturer according to the RCMP G.S. 1045-177 purchase specification. Permission was granted to the manufacturer from the RCMP for this purchase. The armour panels were all size 44-46R, which compares favourably with the average size of the aged armour. A sample of the aged armour was sent to the manufacturer to confirm that the construction would be identical.

The panels were made using Twaron® ballistic fabric and supplied in sealed pouches with Velcro tabs exactly as they would be supplied to the RCMP.

Three groups of armour, each 50 panels, were compared by V50 testing. The first group comprised naturally aged armour returned from the RCMP, the second group was new armour manufactured to the same specification and the third group was new armour subjected to the NIJ-0101.06 environmental conditioning protocol.

Fifty new armour panels were shipped to H.P. White Laboratory, Inc. for environmental conditioning as per NIJ-0101.06, Ballistic Resistance of Body Armour, July 2008. Each armour batch was tumbled for 10 days at 5 rpm at a temperature of 65°C and 80% relative humidity.

The NIJ-0101.06 standard describes 12-shot V50 testing, but for our RCMP samples several different sizes were supplied, some small, and there might not have been enough space for that many shots so instead a 10-shot V50 was done. The V50 was determined using the methodology defined by MIL STD 662F which employs the up-and-down method of velocity adjustment to converge on the V50. The V50 was calculated using the arithmetic mean of an equal number of "highest partial" and "lowest complete" perforation impact velocities within a 40 m/s velocity spread. Note that in some cases up to sixteen shots were necessary to achieve this criterion. The remaining shots that were not eligible for V50 calculation, if any, remained valid as data points in calculating logist perforation risk functions.

All shots were .357 Magnum JSP 10.2 g (158gr). All tests were at ambient temperatures and in dry conditions. All shots were straight on. All panels were tested against a standard clay backing surface of Roma Plastilina clay calibrated as described in NIJ-0101.03.

The mean V50 calculated for aged armour was 477.0 m/s (sd 10.1 m/s), for new armour 483.7 m/s (sd 10.1 m/s) and for conditioned armour 489.1 m/s (sd 12.9 m/s).

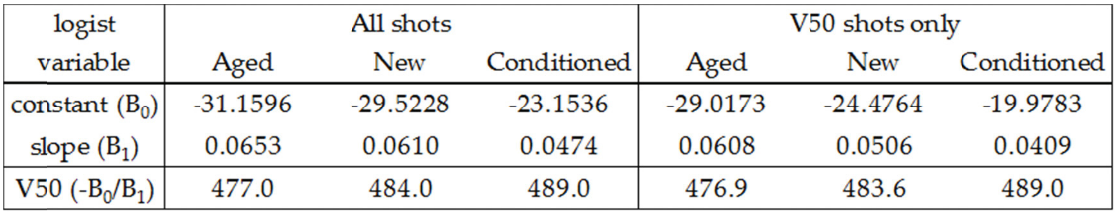
1.3.4.1 V50 by Binary Logistic Regression

Dichotomous data (either perforation or stop) with a general overlap as typically seen in V50 testing can be generalized using binary logistic regression. This generates a probability function to relate the risk of perforation to the .357 projectile's speed. The equation takes the form of

$$p(x) = (1+exp(-B_0-B_1x))^{-1}$$

where B_0 is called the constant and B_1 the slope of the regression model. An add-in module for Microsoft Excel® called XLSTAT was used to calculate the constant and slope variables as well as the 95% upper and lower confidence bounds. These bounds indicate that if additional tests were performed from the same population, the data would fall within this corridor 95% of the time. The efficacy of binary logistic regression and the method for producing the confidence intervals is confirmed by NIST.

Table 7: Logist parameters for V50 armour groups.



logist variable	All shots Aged	All shots New	All shots Conditioned	V50 shots only Aged	V50 shots only New	V50 shots only Conditioned
constant (B_0)	-31.1596	-29.5228	-23.1536	-29.0173	-24.4764	-19.9783
slope (B_1)	0.0653	0.0610	0.0474	0.0608	0.0506	0.0409
V50 ($-B_0/B_1$)	477.0	484.0	489.0	476.9	483.6	489.0

1.3.4.2 Logistic Regression: V50 Shots Only

Using only the ten shots per panel that were used for individual V50 calculations (and ignoring the extra shots taken), the V50 estimations were 476.9 m/s for naturally aged armour, 483.6 m/s for new armour and 489.0 m/s for conditioned armour shown in Figure 14.

At the 50% risk level, the 95% confidence bounds for the aged and new armour just touch each other, suggesting significant difference. The 95% confidence bounds for the new and environmentally conditioned armour overlap, suggesting less confidence in their unique difference. However, the aged and conditioned armour confidence intervals are sufficiently spaced to verify that they are significantly different.

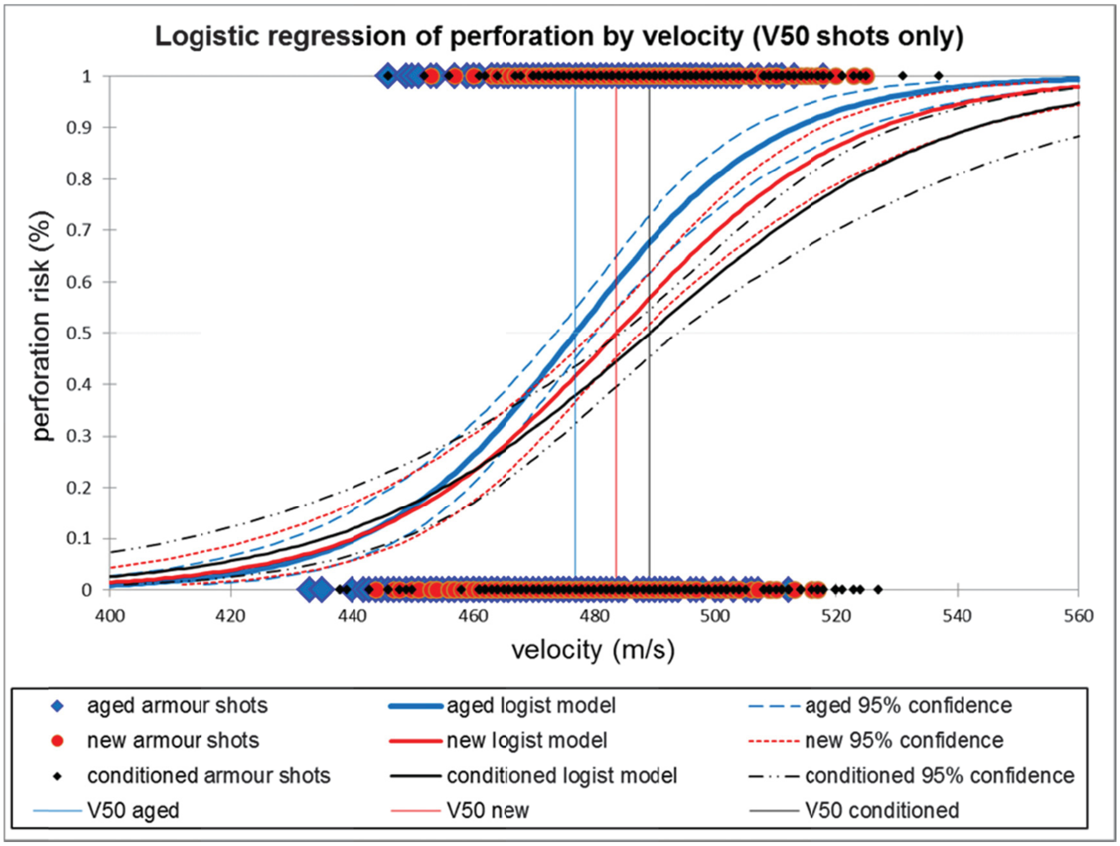


Figure 14: Logistic regression perforation vs. velocity (V50 shots only).

1.3.4.3 Logistic Regression: All Shots

Combining all the shots taken for all panels within each group, the logist curves for the aged, new and conditioned armour were created. The V50 estimations were 477.0 m/s for naturally aged armour, 484.0 m/s for new armour and 489.0 m/s for conditioned armour, virtually identical to the V50 shots only logistic estimates. These are shown in Figure 15.

At the 50% risk level, the 95% confidence bounds for the aged armour are completely separated from both other groups, indicating significant difference. The new and conditioned armour groups have linked confidence intervals, suggesting less confidence in their unique difference.

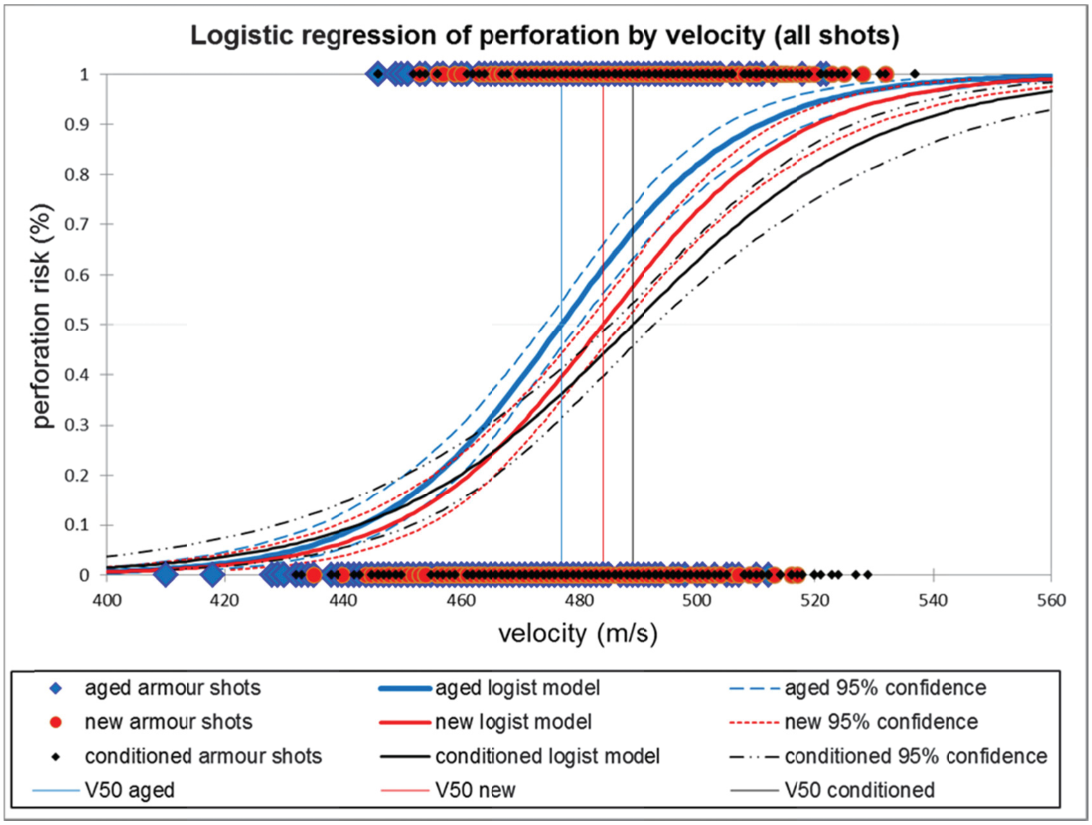


Figure 15: Logistic regression perforation vs. velocity (all shots).

1.3.4.4 Comparison with NIST Results

Whether calculated by arithmetic mean of individual panel V50's or logistic regression estimation, the V50 of aged RCMP armour was significantly lower than new armour by nominally 7 m/s. Intuitively, this is an expected result since it is generally accepted that body armour performance will eventually diminish by some amount in relation to that of new armour.

Environmentally conditioned new armour subjected as per the protocol described in NIJ-0101.06 had an overall V50, whether calculated by arithmetic mean or logistic regression, higher than new by nominally 5 m/s. This result was significant at the 95% confidence level by arithmetic mean, but the confidence curves were linked in logistic regression estimates.

Most importantly in this investigation, the V50 for naturally aged armour was significantly different than the V50 for environmentally conditioned armour by both arithmetic mean and logistic regression. Conditioned armour had a V50 nominally higher than aged armour by 12 m/s. Intuitively this is an *unexpected* result, and suggests that the NIJ-0101.06 conditioning protocol was not effective at simulating the aging process that this particular batch of RCMP field-returned samples experienced.

Had the conditioning process made no difference to the V50 it might have been an interesting result, but the fact that it *improved* the V50 is indeed puzzling. In a comprehensive overview of the NIJ-0101.06 conditioning protocol development, Forester et al. recounted an exhaustive series of experiments with heat, humidity and mechanical agitation and the resulting reductions in fibre strength of PBO (poly(benzoxazole) – Zylon®) and PPTA fabrics. After ten days of exposure, their PPTA armour sample had fibre tensile strength reduction to approximately 85%[5]. Of course, we cannot be sure that our Twaron® fabric, encased in sealed pouches, suffered the same level of humidity exposure as did the NIJ samples, but the heat and tumbling certainly would have been similar.

However, NIST researchers did observe some similar observations with environmentally conditioned PPTA armour in a report on regression models [7]. Although they used probit models, the curves are similar to our logist models, and are reprinted in Figure 16. They found that the conditioning process caused a change in the curve slope that resulted in a V50 shift to the right for conditioned armour (solid red line). Scaling this image yields an estimated V50 increase of roughly 5 m/s, which compares exceptionally well with our observed V50 shift of 5 m/s from new to conditioned armour. But although this might seem like a good thing, the conditioned armour predicted a higher risk of perforation at lower velocities, such as within the typical fair range for certification testing. The conditioned armour also had wider 95% confidence bounds, so the uncertainty in the ballistic performance increases as the PPTA armour is conditioned.

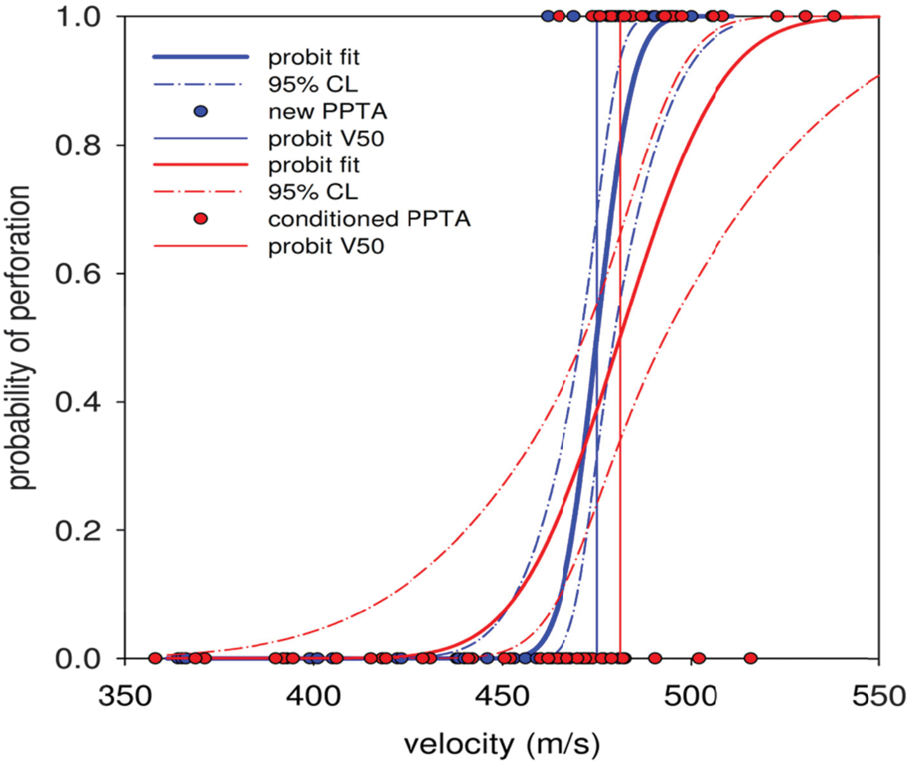


Figure 16: Estimated probit response curves for new and conditioned PPTA armours (reprinted copy from [7])

If we estimate the 5% predicted risk of perforation from our logistic regression model (all shots), we get 436 m/s for new armour, 432 m/s for aged armour and 427 m/s for conditioned armour. These speeds all exist within the fair speed test range for certification. Clearly the confidence bounds of these estimates will completely overlap, but nevertheless it shows a trend dissimilar to the V50 scores. In other words, if V50 estimates were used as a benchmark for armour deterioration, the V05 values would not necessarily follow suit.

A general conclusion by NIST researchers [7] probably gives the best explanation of our findings: "…the conditions selected are found to be quite detrimental to PBO armours of designs that previously had exhibited problems in the field. The conditions have not been found to be excessively detrimental to other commonly used types of armor. However, the protocol does not represent an exact period of time in the field." Further conclusions suggest that continued work to develop laboratory simulations of field-aged armour is necessary.

1.3.4.5 NIJ 0101.06 Environmental Conditioning Summary and Conclusions

The following summary and conclusions have been made following this V50 testing of 50 samples of aged RCMP armour, 50 samples of identically constructed new armour and 50 samples of environmentally conditioned armour.

1. The V50 for conditioned armour was significantly higher than field-returned aged armour. These results are similar to those experienced by NIST in the development of the NIJ-0101.06 protocol. NIST stated that the NIJ-0101.06 conditioning process is effective to expose weakness in PBO armour, but not necessarily other materials such as PPTA. The RCMP panels were made from Twaron®, which is a PPTA.

2. The NIJ-0101.06 environmental conditioning protocol did not mimic the age and wear effects experienced by field-used RCMP armour as evidenced by V50 ballistic test results.

3. Changes in V50 with aged (or conditioned) armour do not necessarily track with changes in V05 and therefore may not give a true estimate of the perforation resistance within the true region of interest for deciding on the continued service life of aged armour.

1.4 Consolidation of Conclusions

The following Table 8 provides a summary of the DRDC contract number, the associated Biokinetics and Associates Ltd. report number, the content of that work and the general conclusion drawn that are pertinent to a revised Aged Armour Purchase and Replacement Protocol.

Table 8: Consolidation of prior work and conclusions towards a revised prototol.

Contract	Bio. Report	Description	Conclusions
NRC direct	R07-16	• OLES response to the Zylon® degradation issue; • Manufacturers' warranties investigated. • availability of aged armour from Cdn police forces • armour replacement policies; • workplan to obtain and test aged armour from Cdn police forces.	• No unified approach among CDN police for decision on when to replace armour; • Warranties are not performance related**. • Latest NIJ standard includes environmental conditioning.
W7701-8-4402 W7701-0-1765 W7701-6-1933 TA65	R09-28 R11-12 R12-11	• 450 service returned Level II armour obtained from 23 Cdn police forces over 3 phases (qty 150 per phase) • P-BFS testing with .357 bullets at speeds below, within and above the NIJ-0101 fair range speeds.	• P-BFS testing revealed no correlation of bullet resistance with age (based on .357 bullets) • Unexpected perforations in young armour and non-perforations in 17-yr old armour suggest that design and construction likely play a larger role in bullet resistance than simply age.
W7701-0-1767 W7701-6-1933 TA64	R11-07 R12-12	• 6-shot V50 testing on 120 back panels matched to first 150 front panels using Minicel® backing (not clay). • Comparison of V50 response on clay vs Minicel® backing.	• V50 did not correlate with age. • Perforation response data from back panels did not correspond with matching front panels. • V50 testing revealed differences between clay and Minicel® explaining this discrepancy.
W7701-6-1933 TA53	R12-19	• V50 testing of field returned armour compared with new and 'environmentally conditioned' armour as per NIJ-0101.06	• V50 of aged armour was slightly less than new armour. • V50 of conditioned armour was higher than new armour. • Shapes of V50 curves did not remain constant and thus influenced the V05 (5% risk). • V50 may not be the ideal criterion for determining future effectiveness of aged armour.
W7701-8-4390	R10-06	• Draft aged armour protocol created	Discussed further in Section 2.

** Note that current armour certified to the most recent NIJ-0101.06 under the NLECTC's compliant products list (CPL) are required to define their warranty in terms of bullet resistance.

2 Review of the Original Draft Protocol

The original draft protocol has been reconsidered in light of the subsequent test programs involving aged armour, as well as conditioned and new armour. Broad revisions to the protocol are outlined below in Table 9. More details are provided in Section 4.

Table 9: General revisions to draft protocol.

Issue	Details in Original Draft Protocol	Revised Approach
Retrospective vs prospective	• No detailed records kept of armour distribution among most police forces. • Initial test data for in-service armour is not available. • Any successful protocol must be prospective.	• Unchanged.
Key Assumptions	• New armour fully meets the requirements of the standard listed on the garment label. • Ballistic performance will degrade measurably over time in a predictable way until it no longer meets certification requirements.	• It is not clear to what level of scrutiny armour certification was held to in the past. Armour certified to NIJ-0101.06 is done under the supervision of the NLECTC. • While it is evident that some degradation must happen eventually, it is not clear how this relates to age and normal use. It is also not clear that V50 testing will illustrate this.
Purchasing	• Manufacturer ISO 9001 • Armour must be certified to NIJ-0101.06. • Manufacturer willing to share certification test records. • Lot must be identical in construction and sufficiently large to justify a tracking program.	• Manufacturer should have QA system based on BA 9000 • Sharing of certification records not necessary since all certified products are listed on a public registry. • Lot details remain unchanged.

Lot acceptance testing	• 12-shot V50 (10-13 panels) • Accept if no perfs < 445m/s and V05 ≥ 436m/s	• V50 testing is used for research, certification and scientific purposes. • Most police forces personnel are not suitably familiar with the mathematical demands of calculating and understanding V50. • There is considerable debate on the mathematical processes of calculating V50. • Police are more interested in the performance of their vests at bullet speeds expected on the street and not complex mathematical probabilities. • P-BFS will be recommended for aged testing acceptance.
Tracking and recall for testing	• Armour from original batch must be tracked and a sample recalled from service for lab testing. • Suggested initially at 5 years then every one or two years after	• Unchanged.
Recalled sample size	• Based on ISO 2859-1:1999	• Based on ‘accept on zero’ defects sampling plan.
Aged sample acceptance testing	• 12-shot V50 (10-13 panels) • Accept if no perfs < 417m/s and $V50 \geq V50_{new}-V_{marg}-15$m/s and V05 ≥ 408m/s	• Use P-BFS test method with water soaked armour. • Sample size based on AOZ plan for tightened inspection. • Accept if no complete perfs.
Consequence of aged test results	• Interpretation of change in V50 not possible without a pilot study	• Any perfs: replace lot. • No perfs, continue using lot 1 more year, then repeat.

3 Consultation with the OLES

In 2003, Attorney General John Ashcroft announced the U.S. Department of Justice's Body Armor Safety Initiative in response to concerns from the law enforcement community regarding the effectiveness of body armour in use. These concerns followed the failure of a relatively new high-tensile fabric used in a vest worn by a Forest Hills, PA police officer [17]. This investigation delved into many aspects of ballistic science and was conducted by researchers at the National Institute of Standards and Technology (NIST). Many of the researchers were part of the Office of Law Enforcement Standards, a division within NIST, who were instrumental contributors to what became the newest revision of the NIJ-0101.06 ballistic standard for personal body armour [12]. Since then the Office of Law Enforcement Standards has been reorganized and key members of that former group are now part of the Security Technologies Group (STG). Those same researchers were kind enough to meet with us to discuss many aspects of determining the useful service life of body armour.

On December 17, 2013, a meeting was held at NIST, 100 Bureau Drive, Gaithersburg, MD. The meeting ran from 09:30h until 17:00h. Attendees included the following:

- Kirk Rice, NIST Security Technologies Group
- Michael Riley, NIST Security Technologies Group
- Amanda Forster, NIST Security Technologies Group
- Dennis Leber, NIST Statistical Engineering Division (SED)
- Jeff Davis, NIST Mathematics
- Laurin Garland, Vernac Ltd.
- Christopher Withnall, Biokinetics and Associates Ltd.

General topics of discussion are reported below.

Review of DRDC Aged Armour Work

A review was given of the aged body armour programs previously conducted, starting with the initial background review of warranty issues, police force replacement policies and availability of aged armour for testing. One of the matters identified in our work was the lack of consistent policy among police forces on when to replace in-service armour. In the Canadian case, that could be as soon as five years all the way up to indefinite service life. The former OLES confirmed that in the United States a similar situation exists among federal police forces (e.g. FBI, DEA, ATF), state police, city police, county police, sheriff's departments and marshal services, each following their own independent purchasing and replacement practices. In some cases officers are given a personal budget for clothing purchase and left on their own to obtain personal body armour. There was some discussion about a Western States purchasing consortium, whereby multiple forces could collaborate for purchasing power of police equipment. However in the majority of cases, purchasing and replacement is left to the discretion of each individual force. Only one force was cited, the New York City Police, that organizes testing to help determine service life.

The former OLES and current Security Technologies Group (STG) has no regulatory authority over policing and does not participate in the certification or subsequent quality assurance of armour in the marketplace. That is managed by the National Law Enforcement and Correction Technologies Center (NLECTC).

We further discussed the results of the P-BFS testing of field returned armour from 23 Canadian Police Forces. These results can be summarized in the two following conclusions: First, age does not appear to correlate with perforation resistance. Second, there is insufficient information available on in-service armour to make any retrospective decisions about the continued service life; in other words any aged armour replacement protocol would need to be prospective.

The former OLES members agreed with these two conclusions, and further confirmed that the design and construction of armour, using well known materials and a sensible quantity of ballistic fabric layers, is the key to effective and long-lasting body armour.

STG Study of Coupons supplied from Phase I, II and III Tested Armour

As part of the cooperative effort between DRDC and the former OLES, the lower 75 mm of armour was cut from 450 P-BFS tested front panels and sent to the OLES. Fibers from these tested panels were extracted for tensile testing. Furthermore a study is underway to investigate the many parameters associated with the armour (e.g. make, model, size, etc.) in relation to bullet perforation. A process called Random Partition Tree Classification Modelling is being used to study these relationships, but no results were reported yet.

Results of the first 150 coupons that were sent to OLES previously are awaiting publication [5].

NIJ Compliance Test Program

The process by which armour is certified to NIJ-0101.06 and the requirements placed on manufacturers to maintain eligibility to stay on the Compliant Products List (CPL) was discussed. Manufacturers must undergo routine quality assurance testing. It was mentioned that when quality checks failed it was almost always due to the tested item being constructed slightly differently than the original certified construction rather than materials being substandard. This supports the notion that new lot acceptance testing is necessary within a purchase and replacement protocol.

P-BFS vs V50 for Protocol

Biokinetics reviewed its results from the DRDC/TSWG test program investigating the NIJ-0101.06 environmentally conditioned protocol. In that it was discovered that conditioned armour actually had a higher V50 than new armour. Discussion about the logist calculations of V50 and the effect on V05 confirmed that our experience was similar to that of the former OLES.

It was agreed that police are not comfortable with the notion of V50 because of the perforations necessarily involved.

It was agreed that a test protocol of P-BFS would be appropriate.

BFS or Not?

In NIJ-0101.06 all shots on new armour as part of P-BFS tests include a measurement of backface signature, and it must not exceed 44 mm (with some statistically based tolerance allowed). For conditioned amour, perforation testing is done at reduced speed and backface signature is not measured nor mandated. There was discussion about the dubious history of the 44 mm, but nevertheless that armour made to this requirement has remained effective in the field. To date there are only two reported fatalities due to backface signature, both due to armours that were grossly overmatched. It was discussed whether or not lot acceptance of new armour should include this requirement, but similar to the conditioned armour test in NIJ-0101.06, it not be a requirement of an aged armour check test.

Sampling Statistics

It is desired that for accepting a batch of armour, a statistical approach be taken in selecting the right quantity of panels for testing and the right number of shots per panel. Like any sampling test program, it is necessary to test a small number of units and infer the quality of the lot based on those results. In the NIJ-0101.06 eight panels are tested in six-shot P-BFS, four at one threat level and four at another. Zero perforations are acceptable, but nevertheless when an armour design's perforation risk is examined using a binomial model, even succeeding with 48 perfect shots still leaves a risk that the next shot might perforate.

The risk of perforation associated with the NIJ-0101.06 standard's 48-shot protocol can be assumed to be acceptable in the certification of new armour.

A lot of new armour of the same make, model and construction may be considered homogeneous even if different sizes exist within that purchase lot. Therefore the results of testing from a sample of that armour can be representative of the lot.

Units from that same lot of armour, after being in field service for some period of time, might not have sustained equal levels of wear and tear. It was discussed that armour in different rigours of service might have degraded differently, and that stratified random sampling should apply in distinguishing between different usage groups. Further discussion about how those groups should be delineated came to no resolution. No scientific evidence exists to distinguish between a well-worn field-used armour and one that saw little use. It was therefore agreed that a random selection at a future time from the initial lot could also be considered homogeneous, and that results from testing that selection could be indicative of the entire lot's continued acceptance.

Tables of upper confidence bound on binomial proportions were reviewed to discuss the numbers of shots necessary to establish similar levels of perforation risk to the original certification testing. This could actually include re-tests of armour that perforates. The exact numbers were not settled in this meeting, suggesting that acceptable risk was a policy decision best left for debate with users, unions and policy makers.

However, different approaches to an aged lot acceptance test were tabled though not selected:

1. Maintain the same bullet velocity range as in certifying new armour, but allow for one or more perforations, perhaps with the necessary retesting of additional armours. This would not be well received by law enforcement despite statistical credibility.

2. Lower the bullet velocity speed (such as done in NIJ-0101.06 conditioned armour) and allow no perforations. This was not strongly supported despite having some precedent in the environmental conditioning requirements of NIJ-0101.06.

3. Follow some form of industrial sampling model, such as ISO 2859-1, MIL-STD 105 or ANSI Z1.4, which define a sample size based on lot size and associated quality defect rates. Again, the acceptable quality was deemed to be a policy decision. Also, many combinations of sample size, lot size and quality designation entailed certain quantities of allowable failures, which would again be uncomfortable for law enforcement.

It was agreed that we would continue to stay in communication as this program progressed.

4 Revised Aged Armour Protocol

The ultimate goal of this protocol is to ensure that ballistic body armour worn by police officers performs as expected. By this we mean that it meets or exceeds the stated ballistic resistance of the current standard on the day of issue, and continues to meet the requirements of that standard throughout its service life. The challenge here, and goal of this protocol, is to help determine the limit of this service life.

The following sections within this chapter discuss the conceptual issues of choosing to adopt a replacement protocol as well as the technical parameters. The final recommended protocol comprises a relatively brief and succinct series of recommended steps, tests and decisions to aid a police force in determining what armour to buy and when to retire it from service. This protocol is provided in Apppendix C, but must be considered a draft until it has been exposed to public comment and debate.

4.1 Protocol Implementation Considerations

The suggested framework for an aged armour replacement protocol begins with the purchase agreement itself and proceeds with a series of verification tests on samples selected from a purchase lot. Obviously the combination of destroyed product and testing fees adds a cost to the initial purchase, and where possible this has been kept to a minimum. However, there is benefit in that the police force gets peace of mind that the purchase lot is compliant and down the road may enjoy extended service life from vests again verified to be continuing compliant.

Current practice re the replacement of aged soft body armour runs the gamut from police services which mandate regular replacement every five years to coincide with the normal five year armour warranty period to those which have no stated policy, replacing armour only when obvious wear or damage indicates, or when a member requires a sizing change or retires from the service. Armour in excess of fifteen years of age is in service in some locations in Canada and some of it performed well in our ballistic tests.

Prior to a police service electing to follow the protocol suggested here for the purchase and replacement of soft body armour, there are a number of factors which will need to be considered, both financial and otherwise. There are some obvious costs, such as the purchase of additional armour for testing and the cost of that testing. However, there are also some potential savings, such as the decrease in life cycle cost due to safely extending the in-service period for a batch of body armour. These costs will depend upon a number of factors which will be explored in more detail in the following section. In addition to financial considerations, there are some factors influencing a decision regarding implementation of the protocol. These might include, for example, any policies already in force which bear on armour replacement.

Factors which might enter into the decision to implement the armour protocol are included in the following sections.

4.1.1 Obtain Known Armour Performance Data

The most significant outcome of using the protocol is that the police service will have actual test data confirming the performance of the body armour in service with its members. This includes newly purchased armour.

The report “Police Body Armor Standards and Testing” carried out by the Office of Technology Assessment for the Congress of the United States, published in August 1992 states in part “NIJ’s certification procedure certifies adequacy of design[18]. It does not assure product quality…. It attests that a few samples of each NIJ certified model did pass a test specified by the NIJ standard and implies other samples could also pass the test if constructed in the same manner as the original samples. But, certification provides no assurance that they are so constructed.” It also notes “Typically, test samples for certification are selected after only a few units have been produced; consequently, the sampling procedure does not guarantee that the samples are representative of yet-to-be-produced units of the model...” Without a mandated quality control program, there is no basis for assuring police that the garments they buy and wear are like the samples NIJ deemed adequate. Thus, while purchase specifications may require supplied armour to be of a model design certified through NIJ, without lot acceptance testing there can be no assurance that the newly purchased armour performs as it should.

During our five year test program, we found examples of NIJ-certified armour in the two and three year old categories which did not perform as required by the then current standard. Since it seems unlikely the armour performance decreased due to aging over such a short time period (well within the five year warranty), our conclusion was that the new armour when purchased did not perform as required by the NIJ standard to which it had been certified.

For armour certified under NIJ-0101.03 and .04, manufacturers’ warranties typically did not warrant ballistic performance (although this point was often missed by purchasers). Rather they were statements about material and workmanship in product construction. The new version of the standard addresses that issue. Under NIJ-0101.06, manufacturers now must actually certify armour ballistic performance for the period of warranty if that armour is to be included on the Ballistic Armor Compliant Products List (CPL) of the NLECTC. Further, the Follow up Inspection and Testing (FIT) program which is now also part of the requirement for having a product listing on the NIJ-0101.06 Compliant Products List does constitute a reasonable quality assurance program and, thus, should reduce the risk of non-compliant certified armour being delivered to a customer. The FIT program requires both regularly scheduled and non-scheduled visits by inspectors to the manufacturer`s premises and testing of samples, pulled from production, for every model of armour on the CPL. It may, therefore, be argued that the warranty is now a satisfactory guarantee of performance.

Nevertheless, without lot acceptance testing, proof of failure of armour to exhibit warranted performance must still come in the form of a bullet perforating in-service armour while being worn by a member of the service.

4.1.2 Armour Warranty

Warranty is a period of time the NIJ Compliance Testing Program (CTP) requires a manufacturer to self-declare and place on the armour label. There are no tests in Standard NIJ -0101.06 that are used to determine warranty period. As a minimum, however, the CTP requires the warranty period stated on the label to represent the length of manufacturer’s warranty period for ballistic performance of the model with the originally declared threat level.

This may give some confidence that the armour will maintain ballistic performance as required by the standard throughout the period of the warranty. Warranty on its own, however, is neither a guarantee of performance nor a reason to retire a product at a specific date.

Warranties typically promise that the manufacturer will repair or replace an item if it is found not to perform to specification during the period of that warranty. That works adequately for a product such as a vehicle where a defect can be repaired to allow the vehicle to return to service. However, as noted above, without acceptance testing a warranty claim within the warranty period must come in the form of a bullet perforating in-service armour while it is being worn. What then is the value of a warranty which replaces that failed item?

On the other hand, as in the previous analogy, many products such as vehicles perform adequately well past their warranty period without decreasing user safety. The same may be true of body armour. Our testing showed that many examples of armour performed to expectation well past warranty expiration.

Acceptance testing and repeated testing of in-service samples per the protocol will allow users to determine the safe lifetime in a scientific manner rather than relying solely on a warranty statement.

4.1.3 Current Replacement Policy

Some police services have adopted a five year automatic armour replacement policy because that coincides with the typical warranty offered by manufacturers. In some cases, this policy has been included in the agreement between the police service and the police member association. If adoption of the protocol is to be possible, appropriate information will need to be provided to the member association, possibly through presentations and Q&A sessions, so that the membership becomes comfortable with the scientific validity of the protocol approach and agrees to sign off on the change in policy. It might be noted that money saved by improving the life cycle of body armour through implementation of the protocol may be available to provide other desired safety-related equipment to the members.

4.1.4 Expected Armour Lifetime

For those police services employing a five year replacement policy, replacement based instead upon the protocol-specified testing program may increase the in-service life of every piece of armour purchased and thus decrease life cycle costs. For those services employing no fixed replacement policy, the opposite may be the case. Testing armour before its normal replacement might show it to be no longer satisfactory. Of course, while such a finding would increase cost to the service, it would also increase the level of safety being provided to officers who otherwise would have been wearing armour which no longer was likely to perform as required. In both cases, the upper limit of in-service life will be determined by the armour eventually no longer performing as required during testing rather than by an arbitrary policy decision. Some of the NIJ-0101.03 and NIJ-0101.04 certified armour we tested showed adequate performance up to fifteen years after manufacture. No data is yet available on the expected lifetime of armour certified to the NIJ-0101.06 standard, however, as that standard was only introduced in 2008 and some time passed before manufacturers offered for sale armour certified to the new standard.

4.1.5 Future New Standards

The current protocol has been written based upon the current version of the NIJ body armour standard, NIJ-0101.06, as well as the Follow up Inspection and Testing regime required for a model of body armour to be listed on the NIJ Compliant Products List. In a document referencing the FIT program published on February 2013, NIJ states as follows: “NIJ anticipates that a Special Technical Committee will begin revising the ballistic-resistant body armor standard in

2013." While the general approach of the protocol should not be affected by a new standard, it will certainly need to be reviewed in the light of any such development.

4.2 NIJ-0101.06 Compliance Test Program

The NIJ-0101.06 was formally introduced in 2008 and supersedes all previous versions of the NIJ-0101 standard. While some police forces may continue to request armour designed to previous versions, and some producers continue to manufacture armour meeting those versions, this protocol development includes only NIJ-0101.06 certified armour, for reasons discussed in the following sub-sections.

The NIJ-0101.06 standard includes five classifications of bullet resistance including armour types IIA, II, IIIA, III and IV. Level IIA is seldom referenced among Canadian police forces, and levels III and IV are hard armour, typically limited to tactical teams, so this protocol will apply only to levels II and IIIA soft body armour for regular officer duty.

This section presumes that the reader has familiarity with the NIJ-0101.06 standard and its predecessors. However, a summary of the numerous changes included in this latest revision is provided in Appendix A. Most notable are the normative inclusion of ballistic limit test (V50), the inclusion of environmental conditioning and the increased number of shots necessary for certification.

4.2.1 Number of Shots vs. NIJ-0101.03 and .04

Analysis of the number of shots required to pass the previous NIJ-0101.03 and NIJ-0101.04 standards shows low statistical confidence due to the low number of shots used to assess the ballistic capability of the armour [3]. These early standards would indeed seem to allow for acceptance of armour based on chance alone rather than on the fact that the low probability of penetration observed is genuine. Recognition of this poor statistical power in earlier NIJ standards is shown in NIJ-0101.06, where the number of shots has been increased for P-BFS and ballistic limit tests as presented in Table 10. For completeness, the 95% binomial confidence bounds are calculated for each version of the standard[6]. For the NIJ-0101.06, we are 95% confident that the failure probability lies between 0% and 9%, which is much better than the NIJ-0101.03 standard where the 95% failure probability lies between 0% and 31%. Based on this information, it is possible that some of the aged armours tested in previous P-BFS investigations would not have passed the more rigorous test methodology in NIJ-0101.06 even if they had been brand new.

Table 10: Failure probability confidence intervals for NIJ-0101.03, 04 and 06 armour.

	P-BFS Tests		Ballistic Limit Tests
Standard	Perforations allowed per total number shots* (perpendicular shots only)	95% confident that failure probability is less than or equal to:	Number of shots used to calculate ballistic limit
NIJ-0101.03	0/8	0.31	N/A
NIJ-0101.04	0/16	0.17	12
NIJ-0101.06	0/32	0.09	120

*note that these counts are per bullet threat and do not include oblique shots.

We can therefore be far more confident in the bullet resistance demonstrated in the certification process for NIJ-0101.06 than for previous versions of the standard.

4.2.2 Certified Products List (CPL) and Follow On Inspection Program (FIT)

Beyond the increased rigour of the NIJ-0101.06 certification test compared with earlier versions, the certification process is carefully managed under the supervision of the National Law Enforcement and Corrections Technology Center (NLECTC). Only laboratories meeting full accreditation with NLECTC are permitted to conduct and submit certification testing[5]. Satisfactory test results and design documentation make a product eligible for the Certified Products List (CPL).

The following is a brief discussion of the NLECTC FIT program for NIJ-0101.06 body armour[6].

4.2.2.1 FIT Purpose

The FIT program is a requirement of the NIJ Compliance Testing Program (CTP) and involves periodic inspection and testing of body armour models previously type tested and found to comply with NIJ-0101.06 Ballistic Resistance of Body Armor[11]. Once a model of body armour is tested and found to comply with the standard, it can be listed on the NLECTC Compliant Products List (CPL). In order for the product to remain eligible to be on the list, the manufacturer must agree to its performance being monitored by a follow-up process that involves periodic selection, inspection and testing of subsequent production samples of the listed model of armour.

4.2.2.2 Frequency of Follow-Up

NLECTC references a Quality Assurance manual specifically for body armour which follows the basic guidelines of ISO 9000. This document is BA 9000[2]. The FIT program recognizes the value of a manufacturer having a Quality Management System (QMS) in place based upon BA 9000. As a result, the minimum frequency of follow up visits has two possible levels. Option1, for companies who do not have a registered BA 9000 QMS, requires that Follow-up Inspection and Testing be conducted at least six times within a 60 month listing cycle. Option 2, for those companies with a BA 9000 QMS, requires a reduced level of three times within the 60 month listing cycle.

---

[5] Note that only American laboratories are eligible for this status.

[6] A full description of the program is given in Document CTP 4-01, Revision 2.0, Implementation 01 May 2011.

After a model has complied with NIJ-0101.06 it is subject to an Initial Product Inspection (the first FIT inspection on a new model). Once this is completed, it is added to the Inspection List. After a model has completed a FIT Cycle it is removed from the Inspection List and, for some period is not subject to further FIT inspections. Following a random period between 8 and 12 months, the model is returned to the Inspection List and once again is subject to FIT inspection.

While a manufacturing location has armour models on the Inspection List, it receives a FIT visit at the following frequency:

• 7 or more models on Inspection List	every month
• 5 or 6 models on IL	every 1-3 months
• 3 or 4 models on IL	every 2-4 months
• 1 or 2 models on IL	as per minimum schedule

Finally, the FIT program also conducts unscheduled inspections. The FIT program document notes that the CTP reserves the right to increase the frequency of FIT for body armour manufacturers who repeatedly fail to produce body amour which passes FIT inspections.

4.2.2.3 Content of FIT Visit

Two samples of each model are identified for inspection and pulled from the production floor. A sample includes both front and rear panels, thus four panels are involved. Initial work includes a visual inspection of samples and a review of build sheets (which fully describe construction and design features of the body armour model under inspection). After this, the selected models are sent to an accredited ballistic test laboratory and tested to a simplified version of the standard ballistic test regime of the .06 standard. FIT testing is limited to perforation testing only. Backface signature is not included. The panels are immersed as per the standard and tested with six shots per panel, as per NIJ-0101.06, with half the shots being taken with each standard test round (one threat round per panel). Finally, a standardized Follow-Up Test Report is prepared.

If a single perforation occurs during the testing, the CTP notifies the manufacturer to fabricate and deliver five additional samples, which are then tested using the same round type that previously perforated the initial sample.

If, during Phase I and Phase 2 testing combined, one perforation or no perforations occur, the model is considered to have passed the requirement. More than one perforation constitutes failure and that model of armor is suspended from the CPL and a series of further follow-ups with the manufacturer is implemented in order to determine and correct whatever deficiency resulted in the failure.

4.2.2.4 Actions as a Result of FIT

Any concerns raised as a result either of the inspection or the testing may result in NIJ issuing an Advisory Notice (within one business day), placing a manufacturing location on Production Hold Status for the specific model (which removes that model from the CPL for the duration), or possibly the immediate withdrawl or suspension of any model of body armour which they determine poses a significant potential risk to end users.

4.2.2.5 Limitations of the FIT Program

Note that the FIT program document itself states: "Follow-up testing reflects only a portion of initial type testing and is therefore not a conclusive indication that production armor would satisfy the full requirements of initial type testing." Further personal communications by the authors with representatives from the FIT program confirmed that the FIT program offered a minimum check and that additional quality assurance measures were advised.

The FIT program aims to ensure that manufacturers continue to produce products having the same design and construction as that which was certified. Samples are inspected and tested to verify that. However, the quantities selected are not necessarily sufficient, nor do the samples subjected to FIT testing necessarily relate to the material supply used to produce a lot of armour purchased by a Police Force on that particular occasion. *Therefore, it is recommended that additional inspection be implemented at the point of lot acceptance*.

4.3 Sampling Considerations

4.3.1 Armour Test Sample Selection

In order for test results from a sample of any product to be used to predict the performance of the rest of a purchase lot of that same product, the sample must be representative of the purchase lot and must be selected randomly from it.

While many designs of body armour are gender neutral, some body armour is available in gender specific designs. While the major design factors such as number of layers of material and types of material may remain the same for gender neutral and female designs, obvious differences in shape, stitching and so on clearly exist. As a result, these armour designs are given different model numbers by the manufacturer, and are certified separately and listed individually on the Compliant Products List. Indeed, the NIJ-0101.06 standard specifically addresses this issue and requires modified test procedures for female specific armour as follows: "For armors that have folds, seams, or other discontinuities (such as the bust cups of some female armors…), additional shots shall be fired so that at least one shot impacts each fold, seam, or discontinuity." As a consequence, such armours would need to be represented by separate samples in any test program. If, therefore, a police service purchases gender specific armour designs for its mix of male and female officers, required testing will need to double in order to represent both designs appropriately.

A major step in assuring that the sample is representative of the entire purchase lot is assuring that all items in the lot and sample are made in the same manufacturing lot, that is, they should all be made to the same design, from the same supplied material using the same process and machines and in a contiguous event, even though that may extend over some time period.

In order to properly protect the wearer, body armour must fit as intended by the manufacturer. As a result, armour is available in a range of sizes. Any typical armour purchase lot will require measurement/sizing of all officers for whom the product is being purchased, and the lot will, as a result, include a number of different sizes of armour. How does one then go about selecting a truly random sample for test? Can one consider the different sizes within a specific model number to be equivalent from the point of view of selection of a test sample? A rigorous statistical approach might argue that, since different size armours are likely to be produced at different times during the manufacturing process, they are not part of one larger homogeneous lot. NIJ 0101.06 addresses this issue by requiring a manufacturer to supply samples of the largest and smallest sizes it intends to produce. By satisfactorily passing tests on these two extremes, the armour design is then certified over this range of sizes. Based upon this approach, we feel it is equally valid to select a random sample from the purchase lot, independent of specific armour size considerations, and declare that the ballistic performance test results from that sample will be valid for the entire lot.

Logistic considerations also impact sample selection. For the initial purchase, the lot will consist of a number of different specific amours sized for and destined for use by specific members. In order to obtain the additional samples required to replace those required for the acceptance test, the planned purchase lot items simply need to be listed and a sequential number starting at 1 assigned to each. A random number generator, numerous of which are available on the Internet, can then be used to generate random numbers for each of the units to be included as part of the acceptance test sample required. These numbers will relate to specific armours which can then be ordered in duplicate as part of the lot purchase to provide immediate replacement armours for those selected randomly for test.

The process for aged in-service armour will be similar but will have the additional constraint that it should be scheduled to coincide with another planned purchase lot so that replacement armours for those randomly selected for test can be added to the new purchase lot. Testing will then need to await the delivery of the replacement armours.

4.3.2 Acceptance Sampling

Acceptance sampling uses statistical methods to determine whether to accept or reject a production lot of material. It has been a common quality inspection technique used in industry. It may be done as products leave the factory or at the point of receipt by the consumer. Most often a producer supplies a consumer a number of items and decision to accept or reject the lot is made by determining the number of defective or nonconforming items in a sample from the lot. The lot is accepted if the number of defects is below the acceptance number otherwise the lot is rejected.

Acceptance sampling is employed when one or several of the following hold:

- Testing is destructive
- The cost of 100% inspection is very high
- 100% inspection takes too long or can be error prone (e.g. boredom of inspector)

Acceptance sampling is "the middle of the road" approach between no inspection and 100% inspection. There are two major classifications of acceptance plans: by *attributes* and by *variables*. For body armour, the aim is to determine whether it stops bullets or not, so attribute based sampling applies.

Each attribute sampling plan has three parameters (N, n, c) which correspond to lot size, sample size and acceptance number respectively. The quality level of a lot is usually expressed as percentage nonconforming (p). The operation of an attribute sampling plan is simple, but there are two types of risk associated with each attribute sampling plan.

1. The first type of risk is that a lot with a high quality level is rejected. We want to accept lots with a high level most of the time. That is, the probability of lot acceptance (Pa) should be high for good-quality lots. However, because of randomness, there is a possibility that the number of non-conforming items found in the sample will exceed c.

This will lead to the decision that a lot of good quality is rejected. This type of risk is the producer's risk, called alpha (*α*).

2. The second type of risk is that a lot with a low quality level is actually accepted. We want to reject such lots most of the time. That is, the probability of lot acceptance (*Pa*) should be low for poor-quality lots. However, because of randomness, there is a possibility that the number of non-conforming items found in the sample does not exceed *c*. This will lead to the decision that a bad quality level lot is accepted. This type of risk is the consumer's risk, called beta (*β*).

There are two ways to calculate the probability of lot acceptance. Suppose that the sampling plan is (*N*, *n*, *c*) and the quality level of the lot is *p*. The first method is an exact method. The number *x* of defectives that are found in a sample will follow a Hypergeometric distribution. The probability of lot acceptance is:

$$P(x, N, n, m) = \sum_{i=0}^{x} \frac{\binom{m}{i}\binom{N-m}{n-i}}{\binom{N}{n}}$$

where *p*(*x*,*N*,*n*,*m*) is the probability of exactly *x* successes in a sample of *n* drawn from a population of *N* containing *m* successes. Note that:

$$\binom{n}{x} = \frac{n!}{x!(n-x)!}$$

is referred to as "*n* choose *x*", and is equal to the number of combinations of size *x* made from *n* possibilities. Also note that 'successes' in our case would really be defective samples. The Hypergeometric sampling scheme is the most exact method because it accounts for the change in lot size remaining after each sample is taken from it. However the factorial calculations make it unwieldy to manipulate and it is generally reserved for smaller lot sizes. It is also called the Type A distribution.

The second method is an approximate method. When the ratio *n*/*N* is small, or the sample is being extracted from a continuous production process where the removal of the sample does not appreciably influence the lot size, the Hypergeometric distribution can well be approximated by the Binomial distribution. The probability of acceptance can be approximated by:

$$P(x, n, p) = \sum_{i=0}^{x} \binom{n}{i} p^{i} (1-p)^{n-i} .$$

where P(*x*,*n*,*p*) is the probability of exactly *x* or fewer successes in *n* trials with a likelihood of success equal to *p* on each trial. The binomial method is also called the Type B distribution.

4.3.3 Operating Characteristic (OC) Curve

These functions are used to create the operating characteristic (OC) curve. The OC curve describes the probability of accepting a lot (*Pa*) as a function of the lot's quality in percent nonconforming (*p*). Figure 17 shows a typical OC Curve.

An OC curve is generally summarized by two points on the curve: the acceptable quality level (AQL) and the rejectable quality level (RQL). RQL is also referred to as lot tolerance percent defective (LTPD). The AQL describes what the sampling plan routinely accepts; formally, it is that percent nonconforming with a 95% percent chance of acceptance by the consumer. The RQL, which describes what the sampling plan routinely rejects, is that percent nonconforming with only a 10% chance of customer acceptance. For the example shown in Figure 17, the single sampling plan n=125 and c=3 (i.e. inspect 125 items and accept on 3 or fewer defects) and has an AQL of 1.1% nonconforming and a RQL of 5.2%. This sampling plan routinely accepts lots that are 1.1% defective or better and rejects lots that are 5.2% defective or worse. Lots that are between 1.1% and 5.2% defective are sometimes accepted and sometimes rejected.

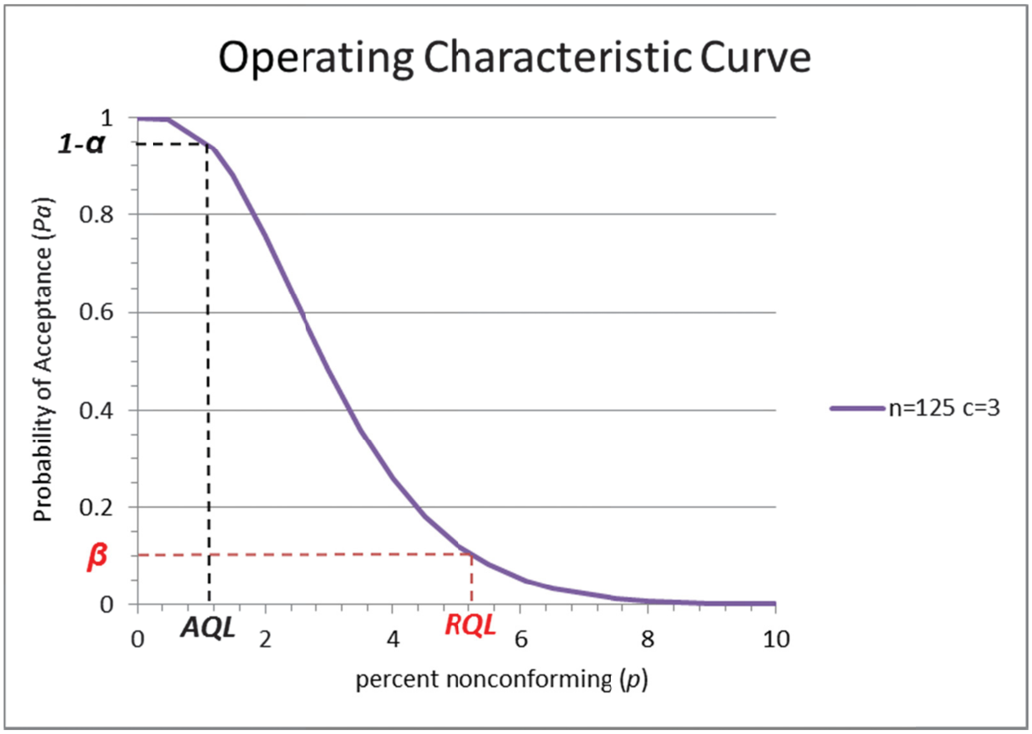


Figure 17: Typical Operating Characteristic (OC) curve.

The first thing to notice about the OC curve above is the shape. As the lot percent nonconforming increases, the probability of acceptance decreases, just as would be expected. Historically, acceptance sampling is part of the process between producer and consumer. To help determine the quality of a process (or lot) the producer or consumer can take a sample instead of inspecting the full lot. Sampling reduces costs, because one needs to inspect or test fewer items than looking at the whole lot.

Sampling is based on the idea that the lots come from a process that inevitably has a certain defect rate. The concept is that the consumer will accept all the producer's lots as long as the process percent nonconforming is below a prescribed level. In a perfect world, this produces the so called ideal OC curve shown in Figure 18. When the process percent nonconforming is below the AQL, the probability of acceptance is 100%. For quality worse than this level, in this example higher than 1.1%, the probability of acceptance immediately drops to 0%.

There are two drawbacks to this approach, however. First, the only way to realize the ideal OC curve is 100% inspection. Secondly, in order to achieve the 'ideal' curve we must increase sample sizes to prohibitive levels, and include defects, which in our case would sanction armours that allow perforations. None of these features is desirable for body armour because of course 100% testing would be pointless, large amounts of testing will be very expensive, and we prefer not to permit failures. More on this will be discussed further along.

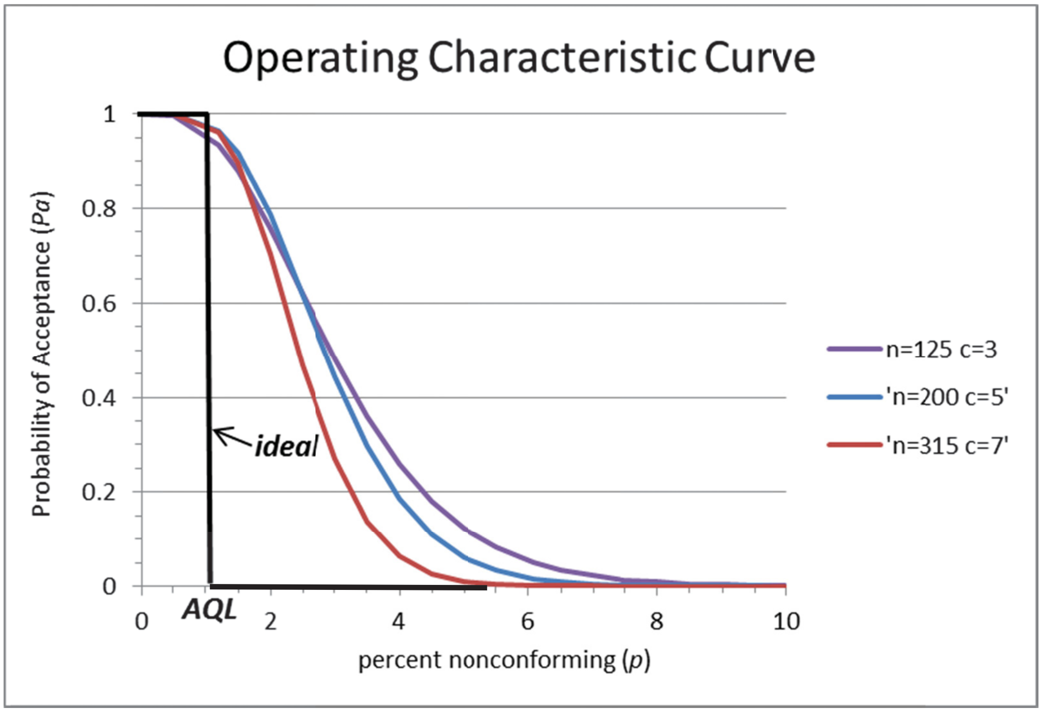


Figure 18: Approaching the 'Ideal' OC Curve

Ideally, any purchase contracting process would define its desired AQL, a reasonable RQL and generate an OC curve through both points that yielded an acceptable number of samples to test and an acceptable number of nonconforming items within the lot. In the real world it does not always work out that way and many sampling plans are directed by AQL alone. Because it is cumbersome to calculate the OC curve for each sampling plan, several industrial sampling plans are available to reference.

4.3.4 MIL-STD-105 Sampling Procedures and Tables

The most widely used plans are given by the Military Standard 105 tables, which were developed during World War II to evaluate lots of munitions. The original version of the standard (MIL STD 105A) was issued in 1950 as a sampling process for lot acceptance by attributes. The last revision (MIL-STD-105E[7]) was issued in 1989, but officially canceled in 1996. By then it had gained widespread popularity among numerous industries, both military and civilian. The tables were reproduced by the American National Standards Institute as ANSI Z1.4[8], the International Standards Organization as ISO 2859-1[9], and the British Standards Institute as BS: 6001: Part1[10].

The aim is to determine the acceptance of a production lot based on the inspection of a small sample from that lot. Inspection by attributes refers to a binary result (either the item is conforming or nonconforming) or the number of nonconformities in an item are counted. For example a bullet resistant armour sampling scheme might involve multiple inspections for stitching, sizing and workmanship defects. However for purposes of this protocol, only bullet resistance will be considered. Other inspection attributes will remain the responsibility of the purchaser.

Tables in MIL-STD-105 give inspection plans for sampling by attributes for a given batch size and acceptance quality level (AQL). The intent is that these plans are used for regular production processes, and AQL refers to the quality level that is the worst tolerable process average when a continuing series of lots is submitted for acceptance sampling. AQL does not mean ’desirable level’. MIL-STD-105 was designed to encourage suppliers to have process averages consistently better than the AQL, otherwise there is a risk of rejected lots and switching to tighter inspection. The aim is to induce a supplier to maintain a process average at least as good as the specified acceptance AQL, while at the same time providing an upper limit for the risk to the consumer of accepting the occasional poor lot. The designation of an AQL does not imply that the supplier has the right knowingly to supply any nonconforming items. In the general case, the AQL will be agreed upon by manufacturer and purchaser and defined in the contracting process.

An inspection plan includes: the sample size/s (n), the acceptance number (Ac), and the rejection number/s (Re). The single sampling procedure with these parameters is as follows: Draw a random sample of n items from the lot and determine the number of nonconforming items within the sample. If the number of nonconforming items is Ac or less, accept the entire batch. If Re or more, reject it. In most cases Re = Ac+1.

4.3.5 Utilizing the MIL-STD-105 Sampling Plan

To utilize the MIL-STD-105 plan, a lot size and an inspection level are selected from the table in Figure 19. Then the corresponding code letter is carried to the right. The code letter determines the sample size and the intersection of the code letter and acceptance quality limit (AQL) reveals the corresponding acceptance or rejection limits. Switching rules may be applied after consecutive lots of acceptable quality, using different tables. A flowchart is provided in Figure 20. Note that in many plans, a certain number of defects are permitted for a given sample size.

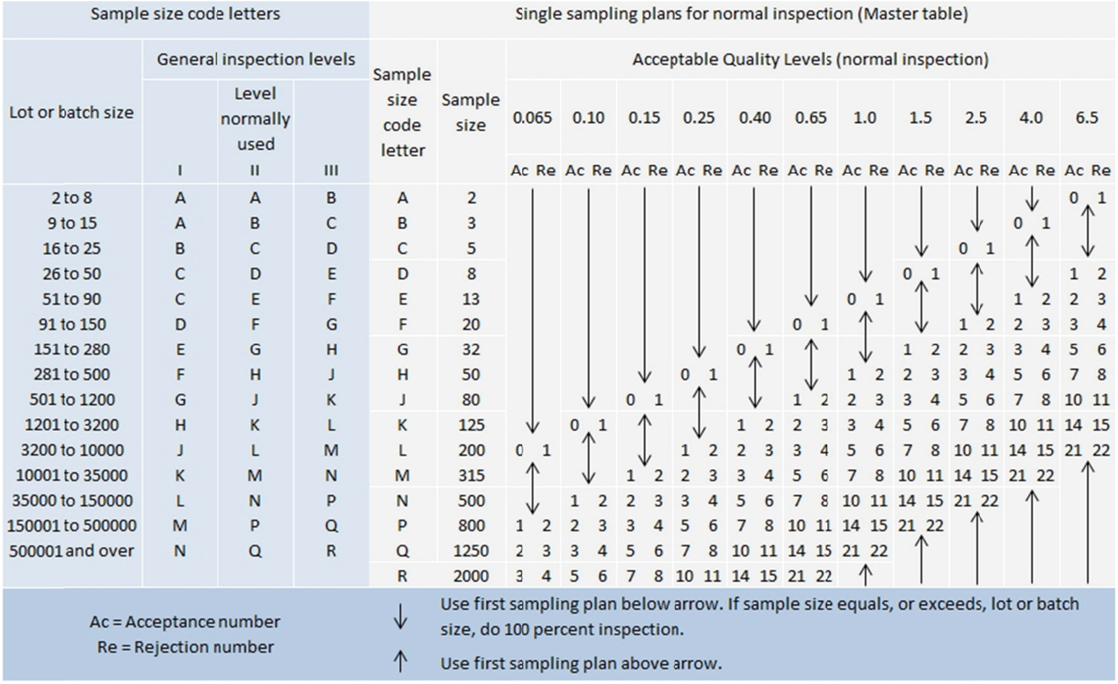
---

[7] MIL-STD-105E: Sampling Procedures and Tables for Inspection by Attributes (10 May 1989). Superseding MIL-STD-105D (29 April 1963).

[8] ANSI/ASQ Z1.4-2008: Sampling Procedures and Tables for Inspection by Attributes.

[9] ISO 2859-1: 1999: Sampling Procedures for Inspection by Attributes – Part 1: Sampling schemes indexed by acceptance quality limit (AQL) for lot-by-lot inspection. 2nd Ed. (15 Nov 1999).

[10] BS: 6001: Part1: 1999: This is a renamed identical version of ISO 2859-1.



Sample size code letters				Single sampling plans for normal inspection (Master table)																							
Lot or batch size	General inspection levels			Sample size code letter	Sample size	Acceptable Quality Levels (normal inspection)																					
	I	Level normally used II	III			0.065		0.10		0.15		0.25		0.40		0.65		1.0		1.5		2.5		4.0		6.5	
						Ac	Re	Ac	Re	Ac	Re	Ac	Re	Ac	Re	Ac	Re	Ac	Re	Ac	Re	Ac	Re	Ac	Re	Ac	Re
2 to 8	A	A	B	A	2																			↓		0	1
9 to 15	A	B	C	B	3																	↓		0	1	↑	
16 to 25	B	C	D	C	5															↓		0	1	↑		↓	
26 to 50	C	D	E	D	8													↓		0	1	↑		↓		1	2
51 to 90	C	E	F	E	13											↓		0	1	↑		↓		1	2	2	3
91 to 150	D	F	G	F	20									↓		0	1	↑		↓		1	2	2	3	3	4
151 to 280	E	G	H	G	32							↓		0	1	↑		↓		1	2	2	3	3	4	5	6
281 to 500	F	H	J	H	50					↓		0	1	↑		↓		1	2	2	3	3	4	5	6	7	8
501 to 1200	G	J	K	J	80			↓		0	1	↑		↓		1	2	2	3	3	4	5	6	7	8	10	11
1201 to 3200	H	K	L	K	125	↓		0	1	↑		↓		1	2	2	3	3	4	5	6	7	8	10	11	14	15
3200 to 10000	J	L	M	L	200	0	1	↑		↓		1	2	2	3	3	4	5	6	7	8	10	11	14	15	21	22
10001 to 35000	K	M	N	M	315	↑		↓		1	2	2	3	3	4	5	6	7	8	10	11	14	15	21	22	↑	
35000 to 150000	L	N	P	N	500	↓		1	2	2	3	3	4	5	6	7	8	10	11	14	15	21	22	↑			
150001 to 500000	M	P	Q	P	800	1	2	2	3	3	4	5	6	7	8	10	11	14	15	21	22	↑					
500001 and over	N	Q	R	Q	1250	2	3	3	4	5	6	7	8	10	11	14	15	21	22	↑							
				R	2000	3	4	5	6	7	8	10	11	14	15	21	22	↑									

Ac = Acceptance number
Re = Rejection number

↓ Use first sampling plan below arrow. If sample size equals, or exceeds, lot or batch size, do 100 percent inspection.

↑ Use first sampling plan above arrow.

Figure 19: MIL-STD-105E for General Inspection levels.

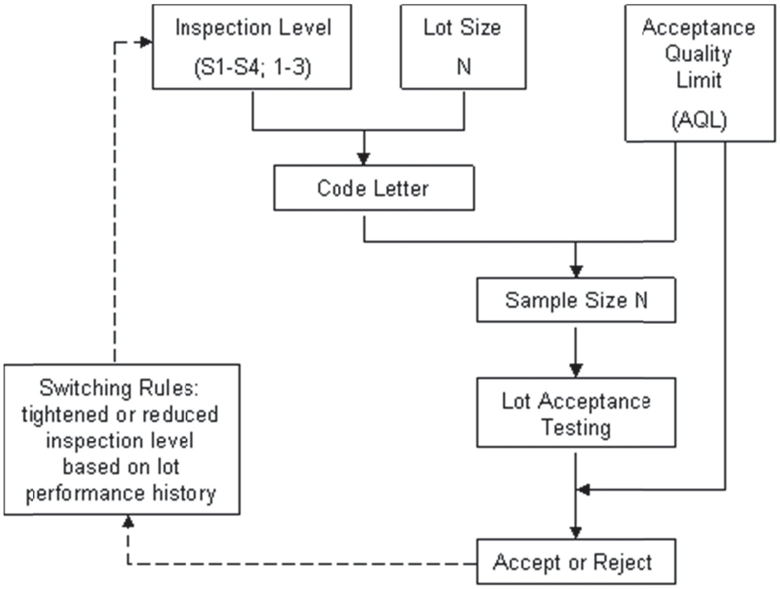


Figure 20: Flowchart for using MIL-STD-105 tables.

4.3.6 Effect of Lot Size in MIL-STD-105

A sampling plan protects both the producer and consumer at risk points agreed on by contract. It is a common misconception that MIL-STD-105 includes lot size because larger lots require more samples to obtain the same level of protection. In actuality 105E takes more samples from larger lots in order to get better protection for the producer. Figure 21 shows the OC curves of several of the 1.0% AQL sampling plans. Increasing lot size increases the sample size letter code which steepens the OC curve resulting in more predictable protection.

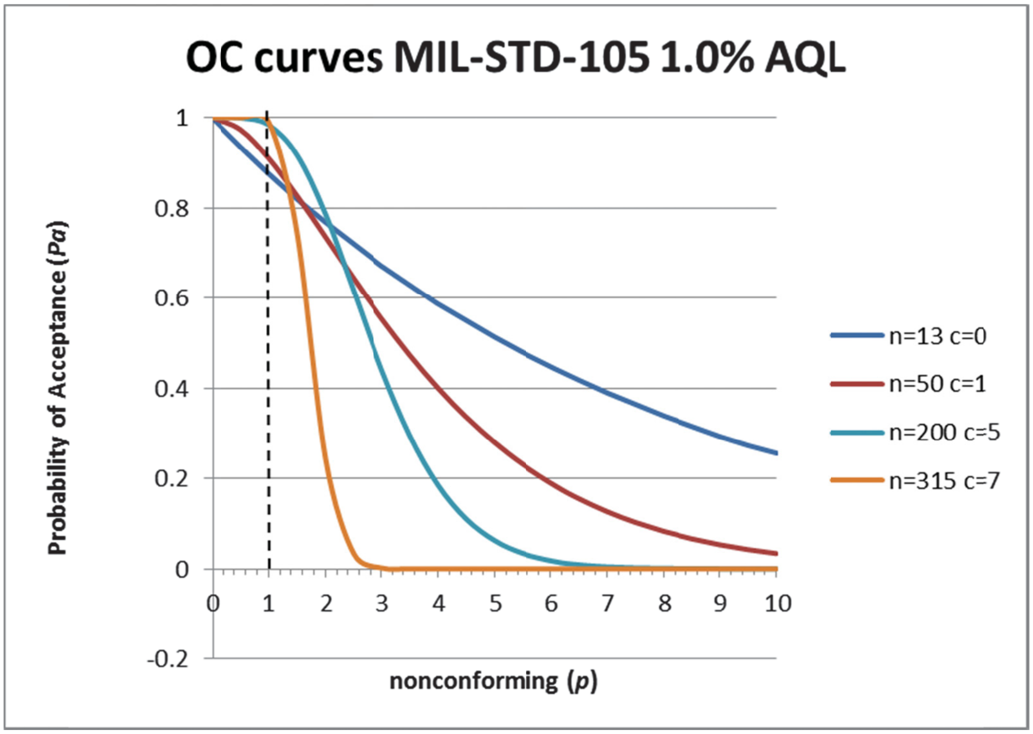


Figure 21: AQL=1.0% OC curves.

Better protection for larger lots can be justified by the fact that for larger lots the costs of rejecting good lots and the costs of accepting bad lots are higher. Since the consequences of making wrong decisions are higher, it makes sense to take more samples to lower the risk of making wrong decisions. While this justification has merit when considering a single product, MIL-STD-105 is used to inspect many different products. Should more samples be selected from a large lot of pencils or from a small lot of body armour? This is why different levels of inspection are offered.

Note that in the above Figure, all OC curves are part of the 1% AQL, but offer probability of acceptance of 88% for the n=13, c=0 plan compared with 99% probability of acceptance for the n=315, c=7 plan. From a manufacturer's perspective, there is more risk of rejection (α) with lower sample size and fewer allowed defects.[11]

4.3.7 Accept on Zero (c=0) Plans

In 1995, the US Department of Defense directed the removal of AQL's from all of its specifications. This resulted in MIL STD 1916 "DOD Preferred Methods for Acceptance of Product". The implementation of this directive also involved the policy that, when lot acceptance is based on only a sample of the total lot quantity, all of the samples should be defect free for

---

[11] It is arguable that higher risk of rejection would encourage better production quality, hence being more desirable for the consumer. Holding the manufacturer's 'feet to the fire' might describe it best.

outright acceptance. That is, only "accept on zero" (AOZ, or c=0) plans are to be used for attributes sampling.

This was done for several reasons. First, a culture had arisen within military supply lines that defects were ‘acceptable’. What reason was there to improve supplier quality when allowable defect counts were built right into contracts? Secondly, accept on zero plans were becoming more popular in industry based on work published by Squeglia [14]. Thirdly, sample sizes were much lower which reduced inspection costs.

At the time accept on zero plans were first introduced, the AQL-based military tables were in widespread use, and AQL’s were commonly referenced in supply contracts. Squeglia determined a series of new OC curves for a given lot size that maintained the same consumer’s risk (β). This was done by finding a c=0 curve that ran through the same RQL as the corresponding MIL-STD-105 plan. An example is shown in Figure 22 for a 4.0% AQL plan of 125 samples accepting on 10 defects or fewer. The probability of lot acceptance is very high at 99% and the RQL is 12.3%. A c=0 OC curve running through the same RQL point exists for a sample size of 18, accepting on zero defects. The new c=0 curve is associated with the old MIL-STD-105 by aligning the RQL associated with the AQL tables, but in fact has a true AQL of less than 1.0%. Higher risk is posed to the manufacturer, but likelihood of accepting a poor lot is decreased for the consumer.

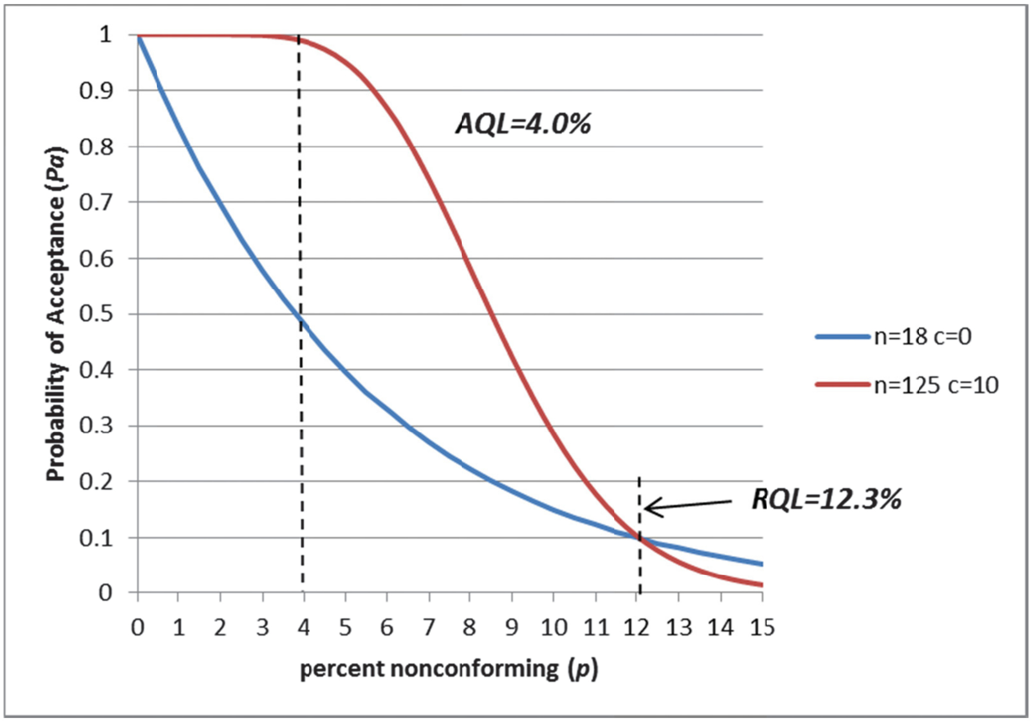


Figure 22: Effects of Acceptance Number on OC Curve.

Clearly the associated c=0 plan required fewer samples to be inspected (in the example 18 vs. 125) and the produce is more inclined to produce good quality to ensure it gets accepted. Most importantly, the culture of accepting defects was changed. Squeglia introduced a new table of ‘associated’ c=0 sampling plans as shown in Table 11. Note that in this reprint associated AQL’s below 0.1 have been omitted, as well as sample sizes above 10,000.

Table 11: Squeglia 'Associated' AQL c=0 Plan (abbreviated table)[15]

	Indexed Values (Associated AQL's)										
Lot Size	***0.1***	***0.15***	***0.25***	***0.4***	***0.65***	***1***	***1.5***	***2.5***	***4***	***6.5***	***10***
	Sample Size										
2-8	*	*	*	*	*	*	*	5	3	2	2
9-15	*	*	*	*	*	13	8	5	3	2	2
16-25	*	*	*	*	20	13	8	5	3	3	2
26-50	*	*	*	32	20	13	8	5	5	5	2
51-90	*	80	50	32	20	13	8	7	6	5	4
91-150	125	80	50	32	20	13	12	11	7	6	5
151-280	125	80	50	32	20	20	19	13	10	7	6
281-500	125	80	50	48	47	29	21	16	11	9	7
501-1200	125	80	75	73	47	34	27	19	15	11	8
1201-3200	125	120	116	73	53	42	35	23	18	13	9
3201-10000	192	189	116	86	68	50	38	29	22	15	9

One caution is raised in accept on zero plans. The MIL-STD-1916 specifically states that it does not apply to destructive tests. This is because the recourse should a defect be discovered is to revert to 100% inspection and investigate the cause of the defect to rectify it. The rejected lot might in some cases be sold at a discount or categorized at a lesser quality and sold elsewhere. In the case of body armour, obviously 100% 'inspection' (in our case ballistic testing) is not feasible, nor would it be right to resell a lot with known defects. This will be discussed further in Section 4.8.

OC curves for each sampling plan above are provided in Annex B, Figure 24 to Figure 31.

4.3.8 Sampling Plan Switching Rules

All the military and industrial sampling plans discussed earlier for inspection by attributes include 'switching rules'. MIL-STD-105 includes three levels of inspection (normal, tightened, and reduced inspection). The type of inspection that should be applied depends on the quality of the last batches inspected. At the beginning of inspection, normal inspection is used. Tightened inspection (for a history of low quality) requires a larger sample size than under normal inspection. Reduced sampling (for a history of high quality) has a higher acceptance number relative to normal inspection (so it is easier to accept the batch). There are special empirically based switching rules between the three types of inspection. The use of switching rules is encouraged because the reward for continued quality is reduced burden of inspection.

MIL-STD-105 further defines four special inspection levels S1-S4. The special inspection levels, as the name implies, are for special situations for which the sample size must be kept small and is otherwise warranted. It also includes double sampling procedures in case the sample taken from the batch is not informative enough, another sample is taken. In this fashion, an initial sample size may be smaller, and if the inspection is acceptable, the second sample becomes unnecessary.

In MIL-STD-105, separate tables are provided for tightened and reduced inspections. However the accept on zero plans of MIL-STD-1916 achieves this by designating a series of quality levels, and tightened or reduced inspection is achieved by moving one quality level column to the left or right. Squeglia achieves a similar result by shifting one ‘AQL’ left or right for tightened or reduced inspection levels[15].

4.4 Purchasing Considerations

4.4.1 Minimum Criteria

The concept of lot sampling relies on the assumption that the lot from which samples are selected is homogeneous. Therefore any armour purchase under this protocol must be held to a high standard of manufacturing excellence. It is expected that many lot purchases for various pieces of police equipment will fall under procurement contracts having detailed item descriptions or specifications. Furthermore, the expectation of manufacturing excellence through adherence to industrial quality models such as ISO 9001 will not be a new concept to larger police forces. Smaller forces, however, who may be more accustomed to smaller purchases through brokers or dealers, may be less familiar with this expectation.

Some minimum criteria for purchasing ballistic vests under the proposed protocol are as follows:

1. Manufacturer should demonstrate an in-house ballistic quality check program (based on BA 9000).

2. Armour model must be currently listed in good standing on the NLECTC’s Certified Products List (CPL).

3. A lot may include different sized vests, but all must be the same model and of the same construction and materials. Note that female models given a specific designation on the CPL must be considered a separate lot and be subject to dedicated lot acceptance testing.

4.4.2 Economy of Lot Size

As with any lot based approach to purchasing, there are economies of scale. In Section 5, “Aged Armour Economic Considerations” it is shown to be particularly true of a testing-based armour replacement protocol. Smaller municipal forces wishing to buy 25 or 50 armour sets in a purchase on their own will not see any economic advantage to using the protocol. It may, however, be possible to work out a cooperative agreement with a larger service or a number of smaller ones to enable larger purchase lots to be assembled. The validity of the statistical approach used to determine test sample quantities which enable inference of the behaviour of the entire purchase lot from the test performance of a representative sample depends upon the purchase lot being a homogeneous population, i.e. it must all be from the same manufacturing lot as discussed above. While certain cooperative purchasing groups do allow smaller forces with smaller purchases to achieve prices equivalent to those granted the larger quantity purchasers, this is not sufficient for application of the protocol. Use of the protocol will require smaller purchases, such as those from a smaller municipal force, actually to be part of a single large purchase at the same time and thus part of the same manufacturing lot. The same logic carries over to any aged armour testing carried out following the initial purchase. If the smaller force individual purchases can now be considered as part of one overall aged sample as a consequence of the initial purchase being part of the same manufacturing lot, the test results will apply to all armour purchased in the original purchase lot, and the test costs may be spread among a number of forces.

4.4.3 Homogeneity of Aged Lots

There is some argument that armour usage across a number of police forces will not be similar and that testing of any one sample of aged armour will, therefore, not represent the performance of the entire aged original purchase lot. Indeed, that argument could be applied to usage within various departments of a single large force (street patrol, vehicle patrol, bicycle patrol, marine division). This would negate the ability of any sample of aged armour to be used to infer the behaviour of the remaining portion of the purchase lot. While this may seem intuitively to be true, there is no published work to date which definitively shows this to be the case. Nor is there any study which shows the effect of different types of usage on aged armour performance. None of our investigations found any area where detailed usage data had been recorded, thus, it was not possible to relate aged armour performance to any measure other than time from manufacture. Failing any scientific validation of the hypothesis that different usage *significantly* affects the performance of aged armour, we believe application of the protocol for aged armour across the full original purchase lot is acceptable. Clearly, this protocol will need to be reconsidered if any future study shows a significant correlation between type of usage and performance of aged armour.

4.4.4 AQL to Determine Acceptance Sample Size

The acceptance quality limit is a standard feature among many military and industrial procurement contracts. As described in Section 4.3 the AQL defines the maximum lot percent defective (e.g. nonconforming product rate) of a purchase quantity. By designating the AQL and the industrial sampling table (e.g. MIL-STD-105E), the sample size to be selected from the purchase lot is determined as a function of that lot size.

So what is an acceptable AQL for body armour? Unfortunately, that is not something the authors of this report are qualified to decide. Typically that would be a policy decision determined through participation of police force senior representatives, union representation and scientific and mathematical expert participation. Obviously too low an AQL, and poor quality armour might be accepted. Too high an AQL and the required sample sizes would be prohibitive, especially for small purchase lots.

Some guidance might be offered by the National Research Council (US) who was tasked with reviewing several scientific issues in relation to the testing of military body armour [10]. In 2009, the US Government Accountability Office (GAO) released a report which commented on the conduct of the test procedures governing acceptance of body armor vest-plate inserts worn by military service members. This GAO report, as well as other observations, led the Department of Defense Director, Operational Test & Evaluation, to request that the National Research Council (NRC) Division on Engineering and Physical Sciences conduct a three-phase study to investigate issues related to the testing of body armor materials. In their analysis, it was determined that a reasonable AQL for armour purchase would be 4.0 in accordance with S-4 inspection level. For lot sizes up to 280, the sample code letters are the same as Level 1 shown in Figure 19. This translates to test sample sizes of 3 for all lot sizes up to 90, accepting zero defects, then sample sizes of 13 for lot sizes 91-500, accepting one defect and rejecting on two. The discontinuity in this sampling plan is a characteristic of the MIL-STD-105 and equivalent plans, which is why the Squeglia sampling plan is more favourable for lot sizes more typical of Canadian police forces.

Since the Squeglia c=0 plans are associated with the MIL-STD-105 plans, we propose to adopt the same AQL=4.0 for new armour as proposed by the National Research Council, but transferring it to the Squeglia tables (see Table 11). The AQL for aged armour will be subject to ‘switching rules’ and move to AQL=2.5.

This selection of AQL is certainly open to welcome debate. Should a different level of inspection be chosen, all subsequent economic calculations will need to be reconsidered (see Section 5).

4.5 Armour Tracking

In order to implement the protocol, a police service will need already to have in place or to implement a new database, which will allow the tracking of all body armour. Data stored will include armour information such as purchase lot and date of manufacture as well model and size, and information on the member to whom it was issued. This is necessary to allow recall of random samples of an armour batch at future times to enable repeated testing of in-service samples. It is also necessary to enable recall for replacement of an armour batch once it is determined through testing that the armour is no longer satisfactory for use. The cost of establishing and maintaining the database up to date will form part of the cost of implementing the protocol.

The test sample pulled back from service must be correctly selected from the original lot. To do this, records of who has what vest must be accurate and up-to-date. In the event that a lot must be recalled from service, it must be clear what officers need to be contacted and issued with new armour.

As a minimum the database will need to include:

- Lot purchase data (make, model, sizes, dates of issue, etc.)
- Sample size calculations
- Lot acceptance test results
- Service personnel issued each vest (2 panels + carrier)
- Date of re-test data and results
- Date of next re-test.

If smaller forces piggyback on the orders of larger forces, cross-departmental information will need to be maintained through centralized databases.

4.6 Lot Acceptance Testing

4.6.1 V50 vs. P-BFS

The NIJ-0101 standard tests armour for two performance measures. The first is Penetration and Backface Signature (P-BFS). This is also often referred to as Vproof. The second is Ballistic Limit (BL), often simply referred to as V50. They are described in the NIJ-0101.04 standard as follows: “The first test series, P-BFS, is designed to measure the overall ballistic performance of the armour according to pass/fail criteria. The second test series, baseline BL determination, is a test to penetration failure and is designed to statistically measure penetration performance.”

For P-BFS testing, a number of specific test rounds are fired at the armour at specified velocities. Penetration of the armour is not allowed and the allowable amount of measured deformation of a clay backing material is also limited in order for the armour to meet the pass/fail criteria.

Because it is not possible to fire a bullet at a precise speed, the standard allows an acceptable test speed range deemed "fair". A fair hit is one where the bullet was traveling within this acceptable speed range. Above the fair speed, a panel might still stop a bullet, but any perforation at overspeed is not deemed a failure and a retest is done. When testing according to the standard, a bullet moving within fair speed range or below must not perforate.

NIJ-0101.03 references a minimum required bullet velocity of 425 m/s, and defines a fair hit as "an impact velocity no more than 50 ft (15 m) per second greater than the minimum required test velocity". This gives a .357 range of 425 to 440 m/s, but the defining velocity is the minimum 425 m/s, not some higher reference number.

NIJ-0101.04 (and the NIJ-0101.06 version) on the other hand defines a reference velocity (Vref) plus or minus a tolerance. For the .357 this is 436 ± 9.1 m/s or in other words from 427 to 445 m/s.

Testing to P-BFS requirements will indicate when aged armour is no longer performing to the requirement, but without the existence of a predictive relationship between ballistic performance and age, it will not allow for foreknowledge based on current test results as to when in the future that non-performance is likely to occur.

For BL testing, the same specific test rounds are fired at the armour, but at varying velocities until it is possible to determine V50. The determination of V50 requires a statistical testing procedure whereby this speed at which a projectile is likely to perforate 50% of the time is discovered. This is found by an iterative convergence of speeds that do and do not perforate. The number of shots required is defined differently in various standards. The more shots involved, the better the statistical confidence in the results.

While earlier versions of the NIJ-0101 standard did not include any pass/fail criteria attached to the BL portion of the testing, the current version, NIJ-0101.06 does link required V50 to P-BFS requirements as follows:

> *"For new condition armors the BL test data shall be analyzed as described in Appendix E (essentially how to develop a logist regression of probability of perforation against bullet speed – see below), and the estimated probability of complete perforation at the corresponding P BFS reference velocity must be less than 5%. In other words, V05 new ≥ V ref, new."*

While the standard does not define a minimum value for V50, it does define a limitation for V05, which is found from the V50 logist curve as the velocity at which the probability of perforation is 5%. The V05 must not be less than the Vref. One might interpret this mathematically as accepting worst case a 95% probability (i.e. 1 - 0.05) that a panel will stop a bullet within the fair hit velocity range. The NIJ-0101.06 standard further defines that no single shot in the V50 testing may perforate within the fair hit range. These requirements are illustrated in Figure 23.

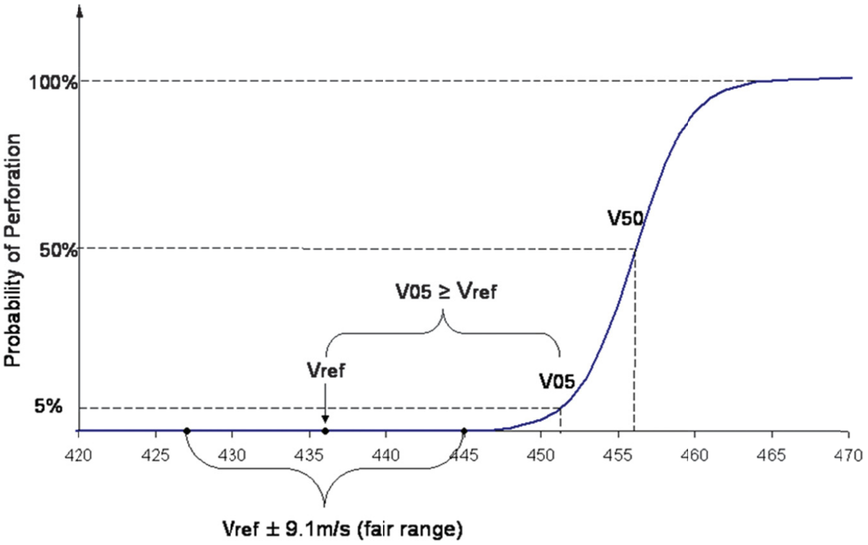


Figure 23: NIJ-0101.06 V05 requirements (example shown Type II, .357)

It is expected that the V50 of aged armour will be less than new. In NIJ-0101.06 Appendix F, a velocity margin (V_{margin}) is defined as:

$$\boxed{V_{margin} = \min\left\{ \begin{array}{c} \hat{V}_{LP,new} \\ \hat{V}(\hat{\pi}_{95\%,up} \leq 0.05) \end{array} \right\} - V_{ref}}$$

which is the lesser value of either $V_{LP}(new)$ (the lowest velocity at which a perforation occurred among all new panels tested) or the $V_{05}(new)$, minus the V_{ref}.

Once this margin has been estimated, *and assuming that the velocity coefficient of the logist performance curve will have remained nearly the same* despite any decline in the armor's overall performance , a minimum allowable aged armor ballistic limit perhaps could be established. The aged V50 should not have degraded more than the degradation margin, but the NIJ states that an additional reduction of 15 m/s might reasonably be allowed to account for the variation in the aged armor ballistic limit estimate. This is not a requirement of the standard, but is suggested as useful in estimating whether armour performance has degraded to the point where its performance may be questionable.

Based on the above, in the original draft version of the replacement protocol, we believed that it might include the following criteria for the acceptance of aged armour:

1. First, there are no perforations within the fair velocity range for conditioned armour.
2. Second, the calculated V50(aged) is greater than V50(new) minus Vmargin minus 15m/s.
3. Third, similar to that of new armour, the V05(aged) remains greater than the P-BFS Vref for environmentally conditioned armour.

It seemed that V50 would be a useful measure of armour performance over time, since it could provide warning of impending failure of the armour to perform in the P-BFS fair hit range. Once V50 fell below the requirements of the NIJ-0101.06 recommendation for aged armour, the armour could be retired, before its performance in the area of interest (V05) became problematic. Our initial design of an armour replacement protocol was, therefore, structured around the use of the V50 test methodology.

Unfortunately, one of the major assumptions of the NIJ-0101.06 standard in this area does not appear valid for all ballistic materials, based both on our test results and supported by NIJ theoretical studies. As described earlier in Section 1.3.4, during our test program to evaluate the suitability of the NIJ-0101.06 environmental conditioning protocol in predicting the behaviour of naturally aged body armour made from fibres other than PBO[12], such as PPTA[13], our test results demonstrated that a shift in V50 as a result of either natural aging or environmental conditioning, did not accurately predict a similar shift in the V05 value, the area of primary interest. In other words, the slope of the logist curve changed as the material aged or became conditioned. This, unfortunately, precludes V50 testing to be used to predict armour performance in the bullet speed range of interest.

4.6.2 V50 vs P-BFS for use in Aged Armour Testing

Ideally, any aged armour replacement protocol would use ballistic testing in such a way as to allow prediction of a future point in time when the performance of a given batch of armour will have degraded to an unacceptable level.

P-BFS testing gives an accurate measure of aged armour performance at any current point in time and the test results can be compared directly to the most recent NIJ standards for armour performance. At present that is NIJ-0101.06 which includes a performance requirement specifically for conditioned armour. In the absence of a known mathematical predictive relationship between armour ballistic performance and age, however, testing to this methodology at one specific point in time cannot be used to forecast when, in the future, a given batch of armour may become unacceptable.

V50 is determined through testing, but the probability of perforation at any other speed is based on a statistical mathematical construct, a logist regression plot of probability of perforation created from the test data. Such plots are known to be less accurate at the extreme ends of the curve, where data is minimal. Add to this the current knowledge that the shape of the logist curve does not necessarily remain constant as armour properties change through conditioning or aging, and the predictive capability of V50 testing for the bullet speed range of most interest (at the V05 speed) becomes quite uncertain.

As a consequence, we believe V50 should not be used as a reliable methodology for predicting the fair hit range performance of aged soft body armour. The only way, therefore, to be sure of the fair hit range performance of body armour is to actually test it using the P-BFS methodology. While one is not able to use current test data to predict future performance, the use of acceptance testing of any new batch purchase to ensure initial performance meets the standard and then retesting at fixed intervals over the lifetime of the armour, will enable P-BFS testing to be used to determine when armour performance has degraded to an unacceptable level. As long as there is a safe margin between the performance limits used to define unacceptable performance and the expected street threats against which the armour will need to perform, as is the case with NIJ-0101.06, this can be a viable methodology for determining the safe lifetime of soft body armour.

---

[12] Poly(p-phenylene-2,6-benzobisoxazole), e.g. Zylon®

[13] Poly(p-phenylene terephthalamide), e.g. Kevlar® and Twaron®

4.6.3 Back Face Signature

As noted above, the NIJ standard for ballistic resistance of body armour tests samples of soft body armour for two different performance measures. One of these is Perforation and Backface Signature, or P-BFS. During testing, the armour panel is mounted on a backing material of a specific type of clay, conditioned through temperature to have a specific consistency and resistance to deformation. When a bullet is fired at the armour, even if it does not perforate, the force of impact and the flexibility of the test sample will result in a depression begin made in the clay at the point of impact. The depth of the deepest point of the depression, measured in relation to the plane of the original smooth flat surface of the clay, is the BFS. The standard limits this to a defined amount. Excessive BFS measurements, even without perforation of the armour, can constitute failure of new armour to perform as required by the standard. This applies only to new designs seeking certification and inclusion on the Certified Products List.

The Follow-Up Inspection and Testing program (discussed in Section 4.2.2), which seeks to monitor ongoing production of new armour to assure a reasonable level of Quality Control exists, selects armour samples from production and subjects them to a modified NIJ test methodology. While the samples are subjected to the same number of shots from the same two standard threats as in the original design certification testing, BFS measurements are not included. As a consequence, we have followed the same example with our Acceptance Testing methodology, as it is a measure of ongoing quality of production, rather than certification of a new design.

For conditioned armour, the NIJ standard states that “excessive BFS measurements will not constitute a failure”. For our testing of aged armour, therefore, we have adopted this same condition, and so will not require measurement of BFS to determine satisfactory performance of the test samples.

4.6.4 Proposed Lot Acceptance Test Method

The FIT program defines an abbreviated NIJ-0101.06 methodology wherein each armour sample, including one back panel and one front panel, undergoes the tests shown below in Table 12. Since Canadian police do not use Level IIA armour, and Level III and IV armour is designated for high velocity rifle rounds, only Level II and IIIA armour are included in this protocol.

Table 12: NLECTC FIT sample test parameters.

NIJ Level	Sample	Conditioning	Panel	Bullet	Speed ± 9.1 m/s	0° angle shots	30° or 45° shots
II	One complete armour	Wet Immersion	1	9mm FMJ RN	398 m/s	4	2
			2	.357 Magnum JSP	436 m/s	4	2
IIIA	One complete armour	Wet Immersion	1	.357 SIG FMJ FN	448 m/s	4	2
			2	.44 Magnum SJHP	436 m/s	4	2

We propose the same testing protocol on each of the required number of samples randomly selected from a lot of newly manufactured armour. The number of samples will be determined by the AQL=4.0 from the Squeglia c=0 plan in Table 11.

4.7 Aged Armour Recall Interval and Sample Size

The recommended time interval for recall of aged armour for testing remains a serious challenge. The HOSDB in the UK suggest that a check on in-service armour be conducted on an annual basis[4]. However their quality model relies on extensive organizational support from the Home Office and an active partnership arrangement with their body armour suppliers. Conversely, early work by the NIJ suggested 10-year old Kevlar® armour remained fully effective[9]. Unfortunately there is limited data to suggest at what age body armour performance has degraded, in fact it is specifically that question that prompted this research.

This issue is discussed extensively by the NIJ Selection and Application Guide to Personal Body Armor[13] , paraphrased in the following notes:

- Age alone does not cause body armor's ballistic resistance to deteriorate….
- NIJ tests failed to demonstrate any significant differences in 10-year old armor, regardless of the extent of use or apparent physical condition…
- In contrast, data from the DuPont study showed that used vests had lesser ballistic performance than new vests. Some vests with marginal performance had been in use for only 3 to 5 years…
- DuPont suggests that testing be considered at between 3 and 5 years of use, but NIJ believes that tests are not necessary until the armor has been in service for 5 years.

Given the rigour of the NIJ-0101.06 certification standard and FIT program, the performance-based manufacturer warranty, along with the lot acceptance check, we believe it is reasonable to test aged armour first after five years of service. Further testing will be conducted yearly thereafter. The database will be used to determine the population of officers to whom armour has been assigned in relation to the original purchase lot. A random selection will be extracted from that lot.

The question then is how many samples should be selected from a lot of aged armour compared with new armour? Our lot acceptance test is on new armour freshly produced from a manufacturing process that has undergone periodic snap inspections and ballistic tests under supervision of the NLECTC. Having passed all these tests, we can be confident that the armour accepted for police use is going to perform as expected. The benefit of the doubt goes to the armour which we expect to pass our acceptance test, and if it does not we assume that the entire lot must be made from a bad batch of material.

But now fast-forward through five years of heat, sweat, flexing, folding, bending and general wear and tear, are we still confident? The answer of course is no, which is precisely why the five-year check is proposed. Our previous study of the environmental conditioning process in NIJ-0101.06 demonstrated that real aged armour did not test exactly the same as environmentally conditioned armour, but that it was an effective means of excluding ballistic materials with known degradation problems (e.g. Zylon®). Simply passing that aspect of NIJ-0101.06 does not give a reliable indicator of future performance. We must assume that the lot of aged armour is an unknown entity, and that it no longer gets the benefit of the doubt. We therefore propose that in order to be confident in its continued service, it must be tested more stringently than when it was initially tested for acceptance.

This concept is similar to the ‘switching rules’ discussed earlier in MIL-STD-105 (see Section 4.3.8) whereby a manufacturer with a known history of good quality can enjoy reduced inspection and conversely one with a history of poor quality suffers tighter inspection. In this case, we are making the assumption that due to age and degradation, our aged armour will be of reduced quality level to that when new. Following a similar approach to inspection by attributes, a tighter inspection level is proposed for aged armour.

In MIL-STD-105, different sample number tables are designated for tightened inspection, but for the accept-on-zero defects plans, Squeglia directs that one AQL shift to the left is equivalent. Therefore since AQL=4.0 was proposed for new armour, one shift to the left of Table 11 to AQL=2.5 is proposed for aged armour sample sizes.

4.8 Consequences of Aged Armour Test Results

The purpose of this entire program is to estimate the performance of a lot of soft body armour based on the test result of samples taken from that lot. It is true that body armour will not stop every bullet at every speed, but the expectation is that armour able to withstand the rigours of the NIJ-0101.06 test program is sufficient to protect officers on the street. It is also true that just because armour was able to survive 48 shots by each of two bullet styles, the 49th shot might still perforate (see Section 4.2.1), although having survived certification, FIT and lot acceptance testing successfully, confidence in that armour will be very high.

Industrial sampling models embrace the mathematics of probability and the understanding that sampling is imprecise, and the only way to be 100% sure of total quality is to conduct 100% inspection. For this reason the c=0 sampling plans are discouraged for destructive testing because the remedy for finding a single defect is to revert to 100% inspection. In most industrial settings a product that fails the c=0 test could be sold at a discount or rebadged as a ‘second’.

With aged body armour, should a defect be found in the sample, we cannot reclassify the armour or sell it at a discount somewhere else. The premise of the aged sample test is that despite the lot being of good design (since it passed NIJ-0101.06) and performing well when new, we are not sure if it can still do the job. Passing the aged sample test with zero perforations confirms that it can. One or more perforations deny it.

Therefore the consequence of any test failure in the aged sample requires the entire lot represented by that sample to be decommissioned and replaced at the earliest opportunity.

5 Aged Armour Economic Considerations

For any police services currently having no stated armour replacement policy, it seems clear that any implementation of a replacement policy based upon regular testing will have an increased cost associated. On the other hand, for those services which currently employ a regular five year replacement of all armour, safely extending the in-service lifetime of that armour through regular testing may be thought to have some positive economic benefits. As a result, the economic analysis which follows illustrates the costs associated with using an armour replacement policy based upon the protocol as opposed to a regular five year replacement with no acceptance testing. While we strongly recommend acceptance testing no matter the replacement protocol used, this comparison gives a worst-case scenario for replacement protocol economics.

Table 13 below defines the variables that were considered in the analysis. Representative values have been used for many of the variables in order to show the effects of varying purchase lot sizes on the economics of using the protocol. Of course, a detailed analysis for a specific situation might see insertion of different values for some or all of these.

Table 13: Variables used in armour purchase cost calcuations.

Variable	Definition	Value
DB	Cost of data base initial set up	\$5,000
Db	Cost of data base yearly maintenance	\$1,000
Tac	Cost of acceptance testing (per armour)	\$600
Tag	Cost of aged armour testing (per armour)	\$600
A	Cost of one complete new armour (two panels plus carrier)	\$700
N	Number of armours in purchase lot	See Table 11
nac	Number of armours in acceptance test sample	See Table 11, AQL=4.0
nag	Number of armours in aged armour test sample	See Table 11, AQL=2.5

In addition, the following conventions and assumptions were used:

- Costs are assessed as at year end.
- Sample sizes and test costs are based upon complete armour samples (two panels).
- Five year replacement takes place in years 6 and 11.
- No testing of aged armour occurs prior to year 6. Yearly testing occurs thereafter.

Based on the above, the following equations were used to describe the yearly costs of the two approaches. For the protocol based approach, year 1 includes replacement armour and testing costs for the acceptance test sample, as well as data base set up and one year of operation. With no testing of aged armour for years 2 through 5, costs are limited to yearly maintenance of the data base. From year 6 onwards, costs are replacement armour and testing costs for the aged armour sample plus maintenance of the data base.

Table 14: Calculations for annual cost estimates.

Cost of 5 year replacement	Years 1, 6, 11	N*A
Cost of protocol based replacement	Year 1	N*A + nac(A+Tac) + DB + db
	Years 2-5	db
	Year 6 and on	nag(A+Tag) + db

To simplify this analysis, we have established what we believe to be representative costs for some of the cost items. Of course, these may well change in future years or for particular applications (for example more expensive armour). The costs for setting up a database, yearly maintenance of that database, testing costs for new and used armour as well as the replacement cost of tested armour are estimated in Table 13. Using these fixed costs and varying purchase lot size, with sample sizes for acceptance testing and aged armour testing as specified in the c=0 tables given earlier, result in the following scenarios for purchase lot sizes of 5, 10, 25, 50, 100, 150, 200, 300 and 500 units, given below in Table 15 and Table 16. Note that costs include both yearly and cumulative totals for comparison.

“Year lot is consumed” indicates the year by which the sum of the aged armour samples equals the amount of the original purchase lot. In other words, all original armour has been consumed by yearly samples retrieved for annual testing.

Table 15: Yearly and cumulative costs for 5-yr versus protocol-based armour replacement for 10, 25, 50 and 100 unit lot sizes (note: shaded cells indicate lot has been fully consumed).

Purchase lot size (N)	**10**				**25**				**50**				**100**			
Sample acceptance (nac)	3				3				5				7			
Sample aged (nag)	5				5				5				11			
Year lot is consumed	7				10				15				14			
Year	**Cost ($ x 1000)**															
	5 yr. plan		Protocol		5 yr. plan		Protocol		5 yr. plan		Protocol		5 yr. plan		Protocol	
	yearly	cum.	yearly	cum.	yearly	cum.	yearly	cum.	yearly	cum.	yearly	cum.	yearly	cum.	yearly	cum.
1	7.0	7.0	16.9	16.9	17.5	17.5	27.4	27.4	35.0	35.0	47.5	47.5	70.0	70.0	85.1	85.1
2		7.0	1.0	17.9		17.5	1.0	28.4		35.0	1.0	48.5		70.0	1.0	86.1
3		7.0	1.0	18.9		17.5	1.0	29.4		35.0	1.0	49.5		70.0	1.0	87.1
4		7.0	1.0	19.9		17.5	1.0	30.4		35.0	1.0	50.5		70.0	1.0	88.1
5		7.0	1.0	20.9		17.5	1.0	31.4		35.0	1.0	51.5		70.0	1.0	89.1
6	7.0	14.0	7.5	28.4	17.5	35.0	7.5	38.9	35.0	70.0	7.5	59.0	70.0	140.0	15.3	104.4
7		14.0	7.5	35.9		35.0	7.5	46.4		70.0	7.5	66.5		140.0	15.3	119.7
8						35.0	7.5	53.9		70.0	7.5	74.0		140.0	15.3	135.0
9						35.0	7.5	61.4		70.0	7.5	81.5		140.0	15.3	150.3
10						35.0	7.5	68.9		70.0	7.5	89.0		140.0	15.3	165.6
11									35.0	105.0	7.5	96.5	70.0	210.0	15.3	180.9
12										105.0	7.5	104.0		210.0	15.3	196.2
13										105.0	7.5	111.5		210.0	15.3	211.5
14										105.0	7.5	119.0		210.0	15.3	226.8
15										105.0	7.5	126.5				

Table 16: Yearly and cumulative costs for 5-yr versus protocol-based armour replacement for 150, 200, 300 and 500 unit lot sizes.

Purchase lot size (N)	**150**				**200**				**300**				**500**			
Sample acceptance (nac)	7				10				11				11			
Sample aged (nag)	11				13				16				16			
Year lot is consumed	18				20				23				36			
Year	**Cost ($ x 1000)**															
	5 yr. plan		Protocol		5 yr. plan		Protocol		5 yr. plan		Protocol		5 yr. plan		Protocol	
	yearly	cum.	yearly	cum.	yearly	cum.	yearly	cum.	yearly	cum.	yearly	cum.	yearly	cum.	yearly	cum.
1	105.0	105.0	120.1	120.1	140.0	140.0	159.0	159.0	210.0	210.0	230.3	230.3	350.0	350.0	370.3	370.3
2		105.0	1.0	121.1		140.0	1.0	160.0		210.0	1.0	231.3		350.0	1.0	371.3
3		105.0	1.0	122.1		140.0	1.0	161.0		210.0	1.0	232.3		350.0	1.0	372.3
4		105.0	1.0	123.1		140.0	1.0	162.0		210.0	1.0	233.3		350.0	1.0	373.3
5		105.0	1.0	124.1		140.0	1.0	163.0		210.0	1.0	234.3		350.0	1.0	374.3
6	105.0	210.0	15.3	139.4	140.0	280.0	17.9	180.9	210.0	420.0	21.8	256.1	350.0	700.0	21.8	396.1
7		210.0	15.3	154.7		280.0	17.9	198.8		420.0	21.8	277.9		700.0	21.8	417.9
8		210.0	15.3	170.0		280.0	17.9	216.7		420.0	21.8	299.7		700.0	21.8	439.7
9		210.0	15.3	185.3		280.0	17.9	234.6		420.0	21.8	321.5		700.0	21.8	461.5
10		210.0	15.3	200.6		280.0	17.9	252.5		420.0	21.8	343.3		700.0	21.8	483.3
11	105.0	315.0	15.3	215.9	140.0	420.0	17.9	270.4	210.0	630.0	21.8	365.1	350.0	1050.0	21.8	505.1
12		315.0	15.3	231.2		420.0	17.9	288.3		630.0	21.8	386.9		1050.0	21.8	526.9
13		315.0	15.3	246.5		420.0	17.9	306.2		630.0	21.8	408.7		1050.0	21.8	548.7
14		315.0	15.3	261.8		420.0	17.9	324.1		630.0	21.8	430.5		1050.0	21.8	570.5
15		315.0	15.3	277.1		420.0	17.9	342.0		630.0	21.8	452.3		1050.0	21.8	592.3

As a result of acceptance testing costs and data base set up, protocol costs are always higher during the first five years. Any positive economics of using the protocol will only occur after the initial five year replacement costs have been factored in. As a result, the yellow highlighted row indicates the first year (after year 5) in which protocol costs exceed the cost of regular five year replacement. This gives a measure of the potential positive economic effect of using the protocol – assuming that testing indicates the aged armour is still safe to use at this point. Then, if one assumes armour test results indicate acceptable performance past the 10 year point, the orange highlighted row indicates the first year (after year 10) in which protocol costs exceed the five year replacement scenario.

Note again that all of these scenarios assume no testing of aged armour is required during the initial 5 year warranty period.

One can see from the scenarios above that the costs associated with using the protocol result in economic benefits for larger purchase lot sizes. For lot sizes of 150 and greater, as testing and data base costs become smaller relative to armour purchase costs, it appears that the protocol replacement approach may have significant positive economic benefits. The full effect of this will, of course, depend upon at what age testing shows that aged armour must be replaced. The benefits will also increase if one uses a larger number for the initial cost of the armour.

For purchase lots around 100 units there seems little economic benefit. If testing shows the armour to be unsafe for continued use by year 9 or 10, there is no economic benefit. If one assumes armour life can be shown to be safe beyond year 11 out to the indicated 13 year financial crossover point, by then it will almost all have been replaced through test sample replacement (lot consumed at 14 years), so one might as well have simply replaced at regular 5 year intervals. While these results are altered by armour pricing used, the effects are minimal.

For any lots smaller than quantity 100, the economics clearly favour a regular 5 year replacement approach, *albeit with attendant risk if not conducting an acceptance check.*

For all of the above, there may well be additional costs associated with the protocol, such as costs of shipping samples to the test laboratory, which are so variable that we were not able to factor them into this analysis. Disposal of samples after testing may cause some incremental cost due to having to handle multiple groups of items, however all purchase lot items will eventually have disposal costs associated with them, just at different times depending upon the outcome of the tests, so we did not consider this as a variable affecting protocol costs.

One might argue that, for smaller purchase lots, the costs used for both data base initial set up and data base yearly operation are not a requirement, as the armour numbers involved are small. On the other hand, testing labs have indicated that for test sample sizes of 5 or smaller, a setup fee would likely be charged in addition to the per lot test cost used in our analysis, so these tend to neutralize each other.

Finally, while 5 year replacement with no aged armour testing may be argued to be a reasonable approach given current NIJ-0101.06 standard's high confidence in design and the NLECTC's FIT program of quality assurance practices, *acceptance testing still offers a reassurance of quality lot acceptance*, as discussed previously. *The authors expressly recommend that an acceptance check be done to verify the quality of the lot.* Obviously this will be a more expensive approach than simply purchasing armour and assuming it is good. Table 17 indicates the costs of acceptance testing alone, based upon the c=0 AQL 4.0 tables.

Table 17: Cost of a 5-yr replacement policy with lot acceptance.

Lot size	sample size	Cost ($ x 1000)		Increase
		5 year	5 year with acceptance test	
N	nac	N*A	N*A + nac(A + Tac)	
10	3	7	10.9	56%
25	3	17.5	21.4	22%
50	5	35	41.5	19%
100	7	70	79.1	13%
150	7	105	114.1	9%
200	10	140	153	9%
300	11	210	224.3	7%
500	11	350	364.3	4%

6 Summary and Conclusions

The following list of general conclusions was used in support of the revised Aged Armour Purchase and Replacement Protocol provided in Appendix C.

- Compared with previous versions of the standard for personal ballistic body armour, the most recent version NIJ-0101.06 requires significantly more shots, an environmental conditioning process, a supervised certification process, a certified products list, performance-based warranty and production quality inspections. It is recommended that only products certified to NIJ-0101.06 be purchased for law enforcement.

- The metric for evaluating the continued performance of aged armour should not be V50. V50 is a useful scientific measure illustrating the ballistic limits of body armour, but does not necessarily communicate to law enforcement exactly how the armour will perform at bullet speeds expected on the street, nor is it necessarily effective to assess degradation of bullet resistance with time. It is recommended that perforation resistance at the fair range of speeds as described by the NIJ-0101.06 standard be used for lot acceptance and future aged armour performance.

- Backface signature is a requirement for certifying new armour, but not mandated in tests for environmentally conditioned armour in NIJ-0101.06. Furthermore it is not measured in the periodic production quality inspection tests supervised by the NLECTC. It will not be recommended to measure BFS in lot acceptance nor aged armour testing. Although it is more economical to perform ballistic testing against a resilient substrate when backface signature does not need to be measured, fluctuations in perforation risk make it preferable to retain the use of calibrated Roma Plastilina clay for all NIJ-based testing.

- A newly revised Aged Armour Purchase and Replacement Protocol has been prepared. It includes perforation testing of random samples from a production lot as a condition of accepting that lot from a manufacturer. It further includes repeated perforation testing of samples from that lot at 5 years, then annually thereafter until either the lot is shown no longer to resist perforation or the lot is depleted to unmanageable levels.

- Sample quantities are based on an ‘accept-on-zero-defect’ or c=0 sampling plan, similar to the type of plans that the US military has now moved towards. A review of the mathematical basis for this plan has been provided. The plan adopts the concept of ‘acceptance quality limit’ to determine the confidence in the accepted product from a manufacturer, and further adopts the same AQL as referenced in US military body armour supply. The concept of switching rules in industrial sampling inspection has been applied to aged armour where a tighter inspection is necessary to account for the unknown condition of that amour from use.

- Some police forces adopt a mandatory replacement policy in which their armour gets decommissioned at some fixed interval, for example five years, regardless of whether or not it remains effective. However, there could be some economic benefit to extending the life of that armour if it does not compromise the officer’s safety. Using some typical costs of armour and commercial testing services, it was shown that our revised protocol is only more economical for lots more than 100. Whether or not a police force adopts a mandatory replacement or a test-based replacement policy, it is recommended that a lot acceptance test be done for every purchase of body armour.

References

[1] Anctil B, Bayne T, Bourget D et al. An Alternative to Plastilina for Evaluating the Performance of Body Armours. Personal Armour Systems Symposium – Brussels, Belgium, 6-10 Oct 2008.

[2] BA 9000: National Institute of Justice Body Armor Quality Management System Requirements. January 2012.

[3] Bourget D, Withnall C, Palmer S, Rice K and Swann S. Aged Body Armour Testing: Further Results. Proceedings of the Personal Armour Systems Symposium 2012.

[4] Dixon C and Croft J. Body Armour Good Practice and Quality Framework. Home Office Scientific Development Branch, Publication No. 44/07.

[5] Forster A, Landais V, Messin G, Riley M, Leber D and Rice K. Field Aged Armor Material Properties Study Phase I Report. US Department of Commerce National Institute of Standards and Technology, March 2011. DRAFT

[6] Horsfall I, Ringrose T and Watson C. A statistical approach to proof testing. Proceedings of the Personal Armour Systems Symposium 2008

[7] Mauchant D, Rice K, Riley M, Leber D, Samarov D and Forster A. Analysis of Three Different Regression Models to Estimate the Ballistic Performance of New and Environmentally Conditioned Body Armor. National Institute of Standards and Technology, NISTIR 7760, February 2011.

[8] Minicel® type L200, Voltek LLC. Density of 32 kg/m3 (2.0 lb/in3).

[9] National Law Enforcement and Corrections Technology Ctr (NLECTC). (1986). Old Armor Tests as Good as New.

[10] National Research Council. Testing of Body Armor Materials: Phase III. Washington, DC: The National Academies Press, 2012.

[11] Phillips J. Body Armor Follow-Up Inspection and Testing. NLECTC Document Identification CTP 4-01, Rev. 2.0. Implementation Date: May 2011.

[12] Rice K., Riley M, Messin G, Petit S, and Clerici C. Development of soft armor conditioning protocols for NIJ Standard-0101.06: analytical results. US Department of Commerce, National Institute of Standards and Technology doc. 7627, 2009.

[13] Selection and Application Guide to Personal Body Armor. NIJ Guide 100-01, 2001. See p61, under Body Armor Life Expectancy.

[14] Squeglia N. Sampling Plans for Zero Defects. Quality Assurance 4 (August 1965): 28.

[15] Squeglia N. Zero Acceptance Number Sampling Plans, 5th Edition. ASQ Quality Press, 2008.

[16] Technical Purchase Description Bullet Resistant Plates for the Canadian Forces, Annex C, Requisition No: W847625701, Document No: 32646-612-21, Nov 15, 2003.

[17] Third Status Report to the Attorney General on Body Armor; Safety Initiative Testing and Activities, Special NIJ Report, August 24, 2005.

[18] U.S. Congress, Office of Technology Assessment. Police Body Armor Standards and Testing: Volume I, OTA-ISC-534 (Washington, DC: U.S. Government Printing Office, August 1992).

Annex A Changes Introduced with NIJ-0101.06

The new NIJ-0101.06 standard features ten basic changes to the previous standards:

1. Five Classification Types: IIA, II, IIIA, III and IV. In addition, there is a special test class that allows armour to be validated against threats that may not be covered by the five standard types.

2. Higher Velocities: The new standard increases the test velocities for new armour testing of Types IIA, II and IIIA. Test velocities have been established for conditioned armour testing. Special-threat rounds have been modified to be tested at elevated velocities within the special test class.

3. Type IIIA Round Changes: Type IIIA lighter weight threat round changed from a 9mm FMJ RN to a .357 SIG FMJ FN.

4. Shot Placement: The new standard modifies “shot-to-edge” spacing to allow shots within two inches of the edge of the vest for the 9mm FMJ RN and .357 SIG FMJ FN threats. The new standard maintains a shot-to-shot spacing of two inches; however, it changes the pattern of the fourth, fifth and sixth shot to be within a maximum of a 3.94” diameter circle.

5. Size of Test Samples: There are now five standardized armour samples that will be accepted for testing to NIJ Standard - 0101.06: smallest, small, medium, large and largest. Two different sizes must be submitted for testing by a manufacturer and the sizes selected determine the range of sizes that can be produced for that particular model.

6. Immersion Testing: The new standard requires test panels to be fully immersed vertically in a water bath at 70˚ F for 30 minutes. The prior standards only required a water spray test for six minutes.

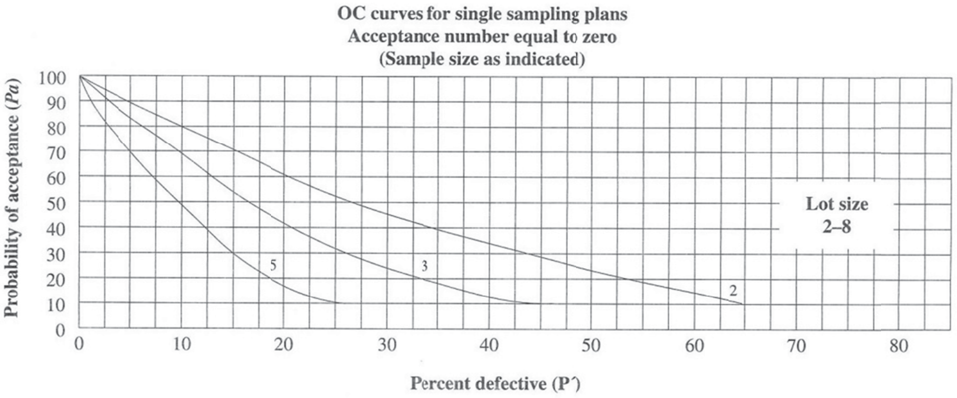
7. Environmental Conditioning (Tumbling) Test: The new standard requires panels to be tumbled for approximately 72,000 cycles over a 10-day period at 149˚ F at 80% relative humidity prior to ballistic testing. The conditioned armour portion of the test protocol uses lower velocities than the reference velocities used with the new armour portion of the test protocol. The prior standard did not include an environmental condition test.

8. Number of Samples Required: The new standard requires 28 complete test samples (front and back panel). The prior standard required six complete test samples.

9. Angle of Incidence: The new standard requires that, for P-BFS testing, each test panel must be shot with one hit at 30˚ and another hit at 45˚ angles.

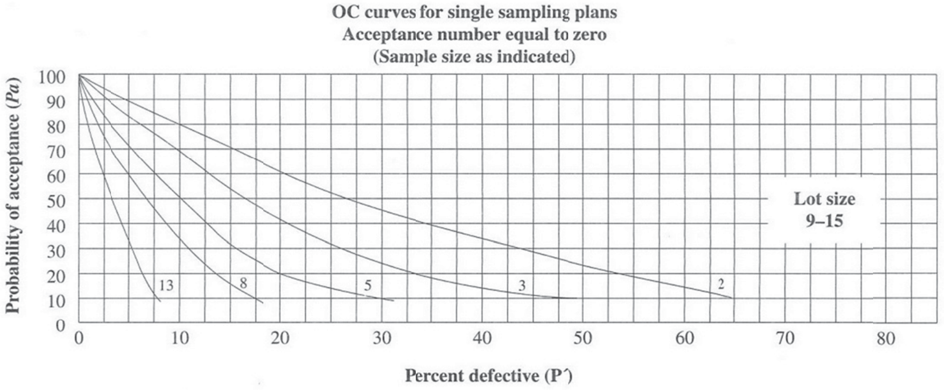
10. Hard Armour Plate Testing (III – IV): The new standard requires hard armour to be tested with uniformed thermal exposure, thermal cycling and mechanical durability testing (drop testing). Each hard armour plate must be submerged in water and tested wet. The prior standard did not require conditioning prior to testing.

Annex B OC Curves for Squeglia C=0 Sampling Plans



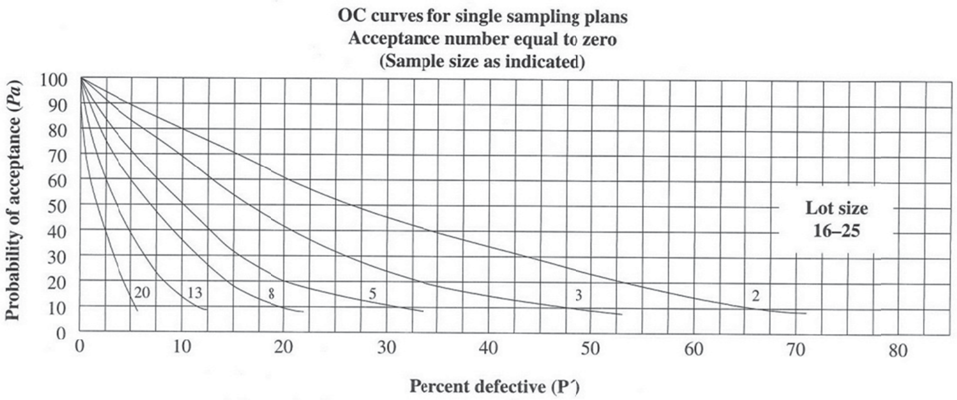
Sample size	Probability of acceptance						
	.10	.25	.50	.75	.90	.95	.99
2	63.7	46.9	27.5	12.50	5.00	2.50	0.50
3	46.7	32.5	18.3	8.33	3.33	1.67	0.33
5	26.0	18.3	10.0	5.00	2.00	1.00	0.20

Figure 24: C=0 plan for 2-8 lot size.



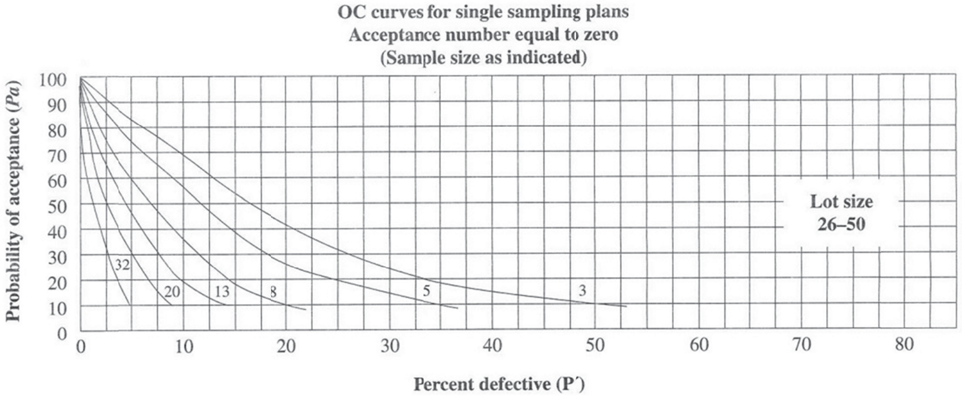
Sample size	Probability of acceptance						
	.10	.25	.50	.75	.90	.95	.99
2	66.00	48.30	28.30	12.90	5.00	2.50	0.50
3	50.00	34.50	19.20	8.61	3.33	1.67	0.33
5	31.80	20.80	11.30	5.00	2.00	1.00	0.20
8	18.70	12.10	6.25	3.13	1.25	0.62	0.12
13	8.46	5.77	3.85	1.92	0.76	0.38	0.07

Figure 25: C=0 plan for 9-15 lot size.



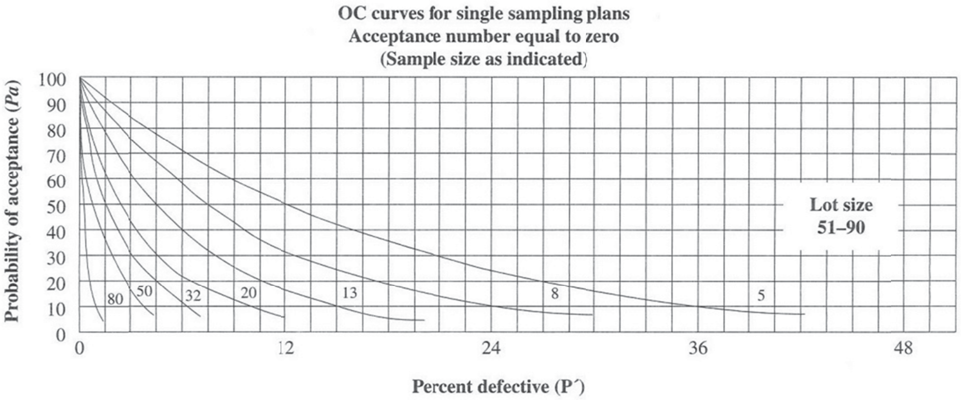
Sample size	Probability of acceptance						
	.10	.25	.50	.75	.90	.95	.99
2	67.00	49.00	28.70	13.10	5.04	2.50	0.50
3	51.40	35.50	19.80	8.80	3.33	1.67	0.33
5	33.90	22.30	11.90	5.20	2.00	1.00	0.20
8	21.40	13.70	7.18	3.13	1.25	0.62	0.12
13	11.90	7.54	3.85	1.92	0.76	0.38	0.07
20	6.40	3.75	2.50	1.25	0.50	0.25	0.05

Figure 26: C=0 plan for 16-25 lot size.



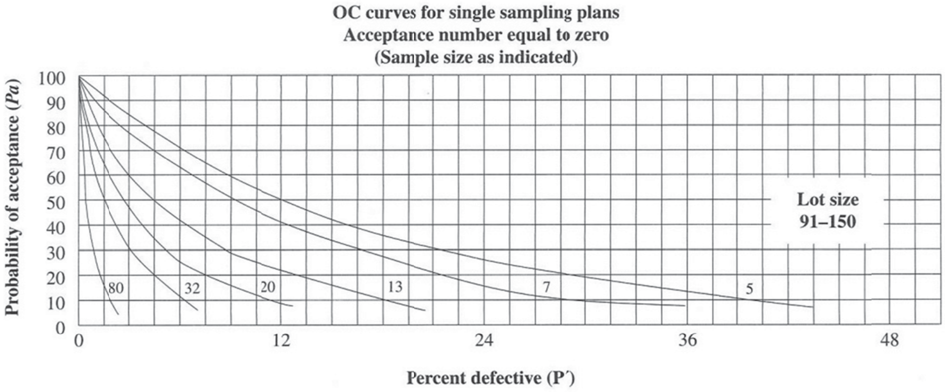
Sample size	Probability of acceptance						
	.10	.25	.50	.75	.90	.95	.99
3	52.50	36.30	20.20	8.97	3.39	1.67	0.33
5	35.40	23.20	12.40	5.38	2.00	1.00	0.20
8	23.20	14.80	7.72	3.31	1.25	0.62	0.12
13	14.20	8.91	4.59	1.92	0.76	0.38	0.07
20	8.73	5.42	2.82	1.25	0.50	0.25	0.05
32	4.60	2.94	1.56	0.78	0.31	0.15	0.03

Figure 27: C=0 plan for 26-50 lot size.



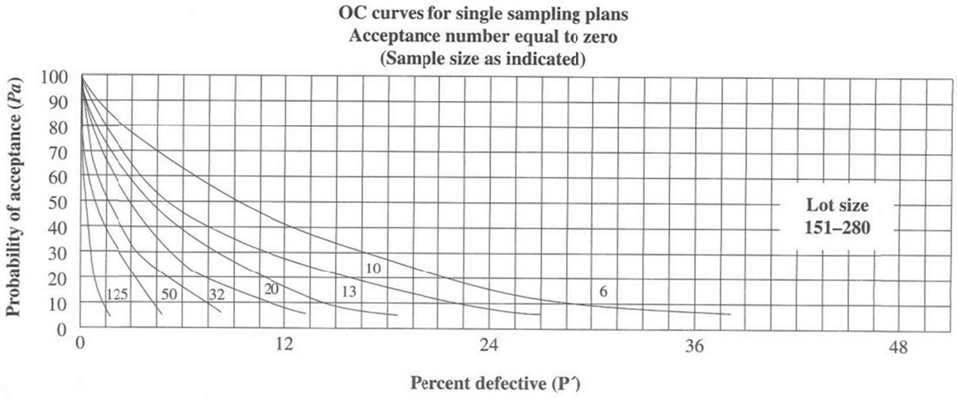
Sample size	Probability of acceptance						
	.10	.25	.50	.75	.90	.95	.99
5	36.10	23.70	12.70	5.47	2.04	1.00	0.19
8	24.00	15.30	7.98	3.39	1.26	0.62	0.12
13	15.10	9.44	4.86	2.05	0.76	0.38	0.07
20	9.70	5.99	3.06	1.29	0.49	0.25	0.50
32	5.68	3.48	1.80	0.78	0.31	0.15	0.03
50	3.17	1.98	1.00	0.50	0.20	0.10	0.02
80	1.23	0.93	0.62	0.31	0.12	0.06	0.01

Figure 28: C=0 plan for 51-90 lot size.



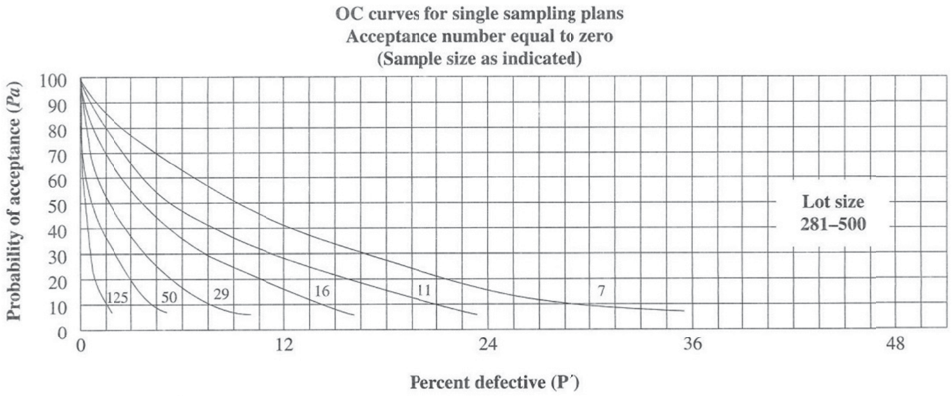
Sample size	Probability of acceptance						
	.10	.25	.50	.75	.90	.95	.99
5	36.40	23.90	12.80	5.52	2.06	1.01	0.19
7	27.50	17.60	9.24	3.95	1.47	0.71	0.14
13	15.60	9.71	4.99	2.10	0.77	0.38	0.07
20	10.20	6.27	3.19	1.34	0.49	0.24	0.05
32	6.21	3.80	1.92	0.81	0.31	0.15	0.03
80	2.00	1.24	0.62	0.31	0.12	0.06	0.01

Figure 29: C=0 plan for 91-150 lot size.



Sample size	Probability of acceptance						
	.10	.25	.50	.75	.90	.95	.99
6	31.60	20.40	10.80	4.64	1.72	0.84	0.16
10	20.20	12.70	6.59	2.79	1.03	0.50	0.09
13	15.90	9.90	5.08	2.14	0.79	0.38	0.07
20	10.50	6.47	3.29	1.38	0.51	0.24	0.05
32	6.55	4.00	2.03	0.84	0.31	0.15	0.03
50	4.10	2.49	1.26	0.53	0.19	0.09	0.02
125	1.39	0.85	0.43	0.20	0.08	0.04	0.00

Figure 30: C=0 plan for 151-280 lot size.



Sample size	Probability of acceptance						
	.10	.25	.50	.75	.90	.95	.99
7	27.80	17.80	9.36	4.00	1.48	0.72	0.14
11	18.70	11.70	6.04	2.55	0.94	0.46	0.09
16	13.20	8.17	4.17	1.76	0.64	0.31	0.06
29	7.41	4.54	2.30	0.95	0.35	0.17	0.03
50	4.28	2.60	1.31	0.54	0.20	0.10	0.02
125	1.59	0.96	0.48	0.20	0.08	0.04	0.00

Figure 31: C=0 plan for 281- 500 lot size.

Annex C Aged Armour Purchase and Replacement Protocol

1. Scope

1.1 This protocol is intended to confirm the minimum acceptable ballistic performance of newly purchased armour by way of lot acceptance testing.

1.2 This protocol is intended to verify the minimum acceptable ballistic performance of aged in-service armour, which had previously passed lot acceptance testing, to determine if extended service life is feasible.

1.3 This protocol is limited to NIJ-0101.06 levels II and IIIA armour.

1.4 Police forces adopting a mandatory replacement policy of fixed duration are advised to adopt the Armour Purchase and Acceptance Testing portions of this protocol.

1.5 The economic benefits of this protocol are limited to lot sizes of approximately 100 or more. This number will vary based on the actual purchase and testing costs as well as the outcome of the aged armour tests.

2. Armour Tracking Database

2.1 Have in place a database tracking system to follow a lot of purchased armour.

2.2 Ensure that the lot number, serial number of each armour panel and recipient officer are linked for retrieval at a later date. The database must include the date of initial lot purchase, date of laboratory testing and lot testing results. The database must have the ability to reassign an armour when previous armour is consumed in sample testing or decommissioned.

3. Armour Purchase

3.1 Purchase only armour certified to NIJ-0101.06 and in good standing on the National Law Enforcement and Corrections Technology Center (NLECTC) Certified Products List (CPL).

3.2 Ensure that the manufacturer engages in an accepted quality management practice, for example ISO 9000 or BA 9000.

3.3 Ensure that each purchase lot is filled by armour produced in one manufacturing lot. Purchase armour in manufacturing lots by model number as indicated in the NLECTC CPL.

3.4 Indicate in the purchase tender and contract that lot acceptance will be based upon successful laboratory test results as described below in *Acceptance Testing*.

3.5 Using a random number generator, randomly select *n* samples from the purchase lot and order a duplicate armour of each. Determine the *new armour* sample number *n* from Table 18 below. These duplicate samples will later be retrieved for ballistic lot acceptance testing.

4. Acceptance Testing

4.1 Upon receipt of each purchase lot, extract the *n* duplicate armours and send them to a qualified ballistics testing laboratory.

4.2 Perforation testing will be performed on the front and back panel of each of the *n* armours.

4.3 The body armour panels will be submersed per Section 7.8.2 of NIJ-0101.06, and six shots per panel will be conducted as is required for the Perforation-Backface Signature testing protocol (NIJ-0101.06, Section 7.8).

4.4 Backface Signature will not be measured as a part of testing.

4.5 Bullet target locations will be as described in NIJ-0101.06, reprinted in Figure 32.

4.6 The threat rounds and velocities will be as indicated in Table 19.

4.7 Complete perforation by any shot at fair speed will constitute a failure and result in complete rejection of that lot.

4.8 Zero complete perforations by any shot at fair speed will constitute a pass and result in acceptance of that lot into service for 5 years.

5. Aged Armour Recall and Testing

5.1 At 5 yrs (+0 yrs/ -6 mos) from the date of original lot purchase, an *aged armour* sample size *n* from Table 18 will be randomly selected from the original lot.

5.2 Officers assigned those armours will be identified and preparations will be made to retrieve their armours back from service. Future lot orders will need to include their replacement units.

5.3 The aged armour sample must be retrieved and submitted to a qualified ballistics testing laboratory 5 yrs (+0 yrs/- 6 mos) from lot acceptance.

5.4 The body armour panels will be submersed per Section 7.8.2 of NIJ-0101.06, and six shots per panel will be conducted as is required for the Perforation-Backface Signature testing protocol (NIJ-0101.06, Section 7.8).

5.5 Backface Signature will not be measured as a part of testing.

5.6 Bullet target locations will be as described in NIJ-0101.06, reprinted in Figure 32.

5.7 The threat rounds and velocities will be as indicated in Table 19.

5.8 Complete perforation by any shot at fair speed or lower will constitute a failure. Replacement of all units from the initial purchase lot must be initiated immediately.

5.9 Zero complete perforation by any shot at fair speed or lower makes the lot eligible for Continued Service (see below).

6. Continued Service

6.1 At 1 yr (+0 yrs/-6 mos) from the date of previous aged recall, an *aged armour* sample size *n* from Table 18 will be randomly selected from the original lot. The *n* is based on the original lot size, not the residual size of a depleted aged lot.

6.2 Officers assigned those armours will be identified and preparations will be made to retrieve their armours back from service. Future lot orders will need to include their replacement units.

6.3 The aged armour sample must be retrieved and submitted to a qualified ballistics testing laboratory 1 yr (+0 yrs/- 6 mos) from previous aged recall test.

6.4 The body armour panels will be submersed per Section 7.8.2 of NIJ-0101.06, and six shots per panel will be conducted as is required for the Perforation-Backface Signature testing protocol (NIJ-0101.06, Section 7.8).

6.5 Backface Signature will not be measured as a part of testing.

6.6 Bullet target locations will be as described in NIJ-0101.06, reprinted in Figure 32.

6.7 The threat rounds and velocities will be as indicated in Table 19.

6.8 Complete perforation by any shot at fair speed will constitute a failure. Replacement of all units from the initial purchase lot must be initiated immediately.

6.9 Zero complete perforation by any shot at fair speed or lower makes the lot eligible to repeat Continued Service.

Table 18: Armour sample quantities by lot size for new and aged armour testing.

Purchase lot size	Sample size *n*	
	New armour	Aged armour
2-8	3	5
9-15	3	5
16-25	3	5
25-50	5	5
51-90	6	7
91-150	7	11
151-280	10	13
281-500	11	16
501-1200	15	19

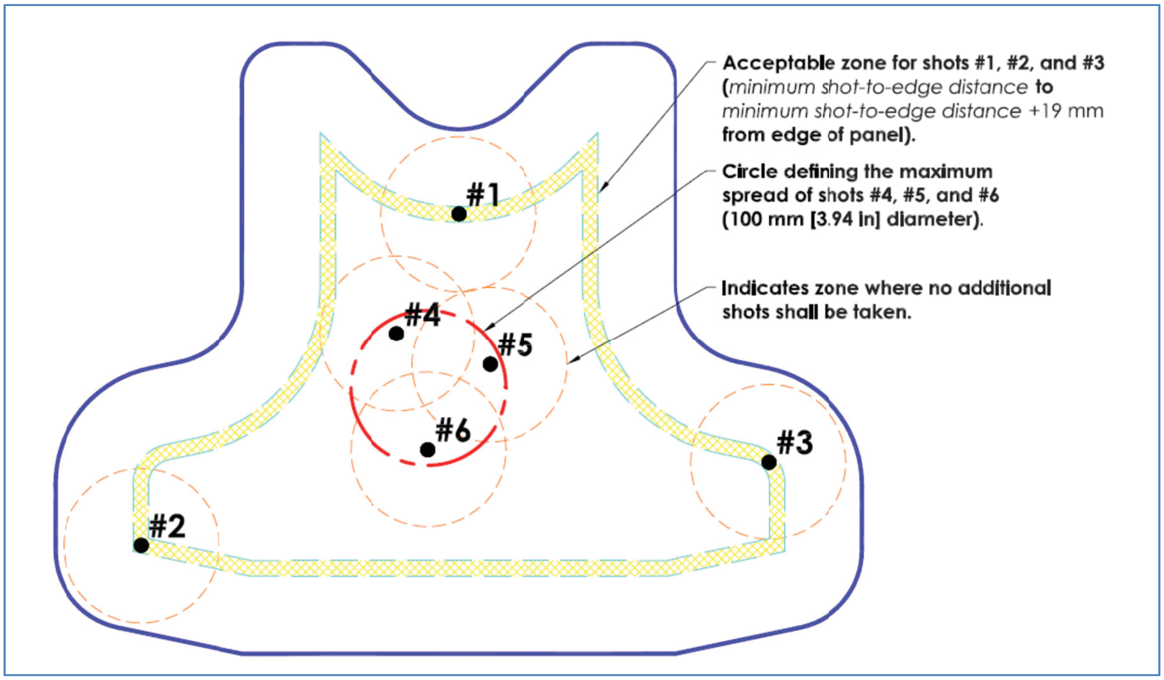


Figure 32: General armour panel impact locations (front and back, minimum shot-to-edge distance = 51mm)

Table 19: Shot schedule for Level II and IIIA armour.

NIJ Level	Panel	Bullet	Mass (g)	Speed (± 9.1 m/s)	Shot No.	Angle
II	Front	9 mm FMJ RN	8.0	398	1, 2, 3, 6	0°
					4	30°
					5	45°
	Rear	.357 Magnum JSP	10.2	436	1, 2, 3, 6	0°
					4	30°
					5	45°
IIIA	Front	.357 SIG FMJ FN	8.1	448	1, 2, 3, 6	0°
					4	30°
					5	45°
	Rear	.44 Magnum SJHP	15.6	436	1, 2, 3, 6	0°
					4	30°
					5	45°

This page intentionally left blank.

List of symbols/abbreviations/acronyms/initialisms

AQL	Acceptance Quality Limit
BFS	Backface Signature
CACP	Canadian Association of Chiefs of Police
CPL	Certified Products List
CPRC	Canadian Police Research Centre
CTP	Compliance Test Program
DRDC	Defence Research and Development Canada
FIT	Follow-On Inspection and Testing
GAO	Government Accountability Office
LTPD	Lot Tolerance Percent Defective
NIJ	National Institute of Justice
NLECTC	National Law Enforcement and Corrections Technology Center
OACP	Ontario Association of Chiefs of Police
OC	Operating Characteristic
OLES	Office of Law Enforcement Standards
P-BFS	Perforation – Backface Signature
RCMP	Royal Canadian Mounted Police
RQL	Rejectable Quality Limit
V50	Velocity at which probability of perforation is 50%