Extended Life Analysis (ELA) of Ceramic Plates

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Abstract. When any piece of personal armour exceeds the life of any warranty given, questions arise as to whether it can still be used or whether it should be replaced. In many cases armour that has reached the end of its warranty period, especially if that period is 10 or more years, can be considered to be obsolete, and perhaps should be considered for replacement on technology terms. However, some users will have armour which they are content to use for significantly longer than the warranty period, if they can be confident that it will still perform at a suitable level. Extended Life Analysis (ELA) is a method of testing which provides a numerical output for an armour system, which was probably originally specified with only a pass / fail type proof velocity criteria. Although not known as ELA at the time, this method was used extensively by UK MOD during the late 90s for specialised armour systems, for which potential replacement systems were not deemed to meet the wider requirements. This particular study, which is currently only into Year 2, consists of the ELA of a large batch of body armour plates which now date back as far as 2005 manufacturing dates. The user acknowledges that they are of an obsolete construction, albeit a very robust one, but due to their particular operations would prefer to continue to use them, rather than replace them. The plates spend most of their time being stored or in the back of vehicles and are only worn occasionally. The plates were originally specified to NIJ-0101.04 Level IV, and hence this is the standard used for the evaluation. The short annual test programme, consists of a small number of plates from which three separate results are acquired. For the ELA a V_{50} across the plates is achieved using 4, 6 or 8 shots. This value is compared with the values from previous years. From the same shot data, it is expected that there will be a number of proof shots, to prove that the plate still meets the NIJ-0101.04 level IV proof requirement. Finally, the user will probably never come up against a 30.06 AP M2 bullet, and so to provide them with some real world confidence, one of the plates will have three factory charge 7.62 x 39 mm PS ball fired into it. This paper outlines the latest test, and describe the successes, but also the limitations, of this approach to ELA of ceramic plates.

1. INTRODUCTION

Many items purchased by people in their everyday lives are supplied with a warranty. For example, in the UK, if a car is purchased new, it will be sold with a warranty covering a specific time, quite often 3 years. When the warranty expires there is the possibility of purchasing an extended warranty for a further period of time, but this is at the discretion of the purchaser. It is rare for items, such as cars, to be disposed of because they have reached the end of their warranty period. A car is a life-critical piece of equipment, so how does the owner know that it is still safe to use after the warranty has expired? In the UK, the car has to undergo an MOT test on an annual basis, from year 3 on, to allow it to still be used on the road, which also gives the owner, a level of confidence that it is safe to use. The MOT test is a predominantly visual test and should, in theory, be a non-destructive test.

Ideally personal armour should also be subjected to a non-destructive test, and there are methods that are used for ceramic-faced armour plates. However, these methods, such as x-ray and ultrasonics [1, 2], may identify damage such as ceramic cracks or composite delamination, but will not determine if the individual material components have degraded. Therefore, although they can investigate damage to the plate, they cannot determine if any of its performance is lost due to material degradation. Material degradation is caused by the aging process of the material and the effects of the environment over time. Various studies have considered both natural and accelerated aging assessments of typical ballistic fibres such as ultra-high molecular weight polyethylene (UHMWPE) or para-aramid, and some of this work was presented in 2012 by Bourget [3], Padovani [4] and Schaap [5].

When any piece of personal armour exceeds the life of its warranty, questions arise as to whether it can still be used or should be replaced. In many cases armour that has reached the end of its warranty period, especially if it is 10 or more years, is probably obsolete technology, and could be considered for replacement. Most items manufactured and sold with a warranty, are assumed to have a life much greater than the warranty period. However, personal armour is usually considered differently.

Despite the tendency for many users to consider that the warranty of personal armour equates to the expected life of the item, some users will have armour which they are content to use for significantly longer than the warranty period, if they can be confident that it will still perform at a suitable level.

Extended Life Analysis (ELA) is a method of testing, which provides a numerical output for an armour system, which was probably originally specified with only a pass / fail type proof velocity

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criterion. Although not known as ELA at the time, this method was used extensively by UK MOD during the late 90s for specialised armour systems, for which potential replacement systems were not deemed to meet the wider requirements.

2. REASON FOR THIS STUDY

This particular study, which is currently only into Year 2, consists of the ELA of a large batch of body armour plates, which date back as far as 2005 manufacturing dates. The user acknowledges that they are of an obsolete construction, albeit a very robust one, but due to their particular operations would prefer to continue to use them, rather than go to the expense and effort of replacing them. These particular plates spend most of their time being stored, or in the back of vehicles, and are only worn very occasionally. They are also stored and transported in a climate where there can be a huge difference between day and night-time temperatures.

3. CERAMIC PLATES TO BE TESTED

The ceramic plates were originally specified to NIJ-0101.04[6] Level IV, and hence specific requirements of this standard are used during the evaluation. These requirements included the mounting of the plates for all tests, upon a conditioned, calibrated and formed Roma Plastilina Number 1 backing, the specific Level IV ammunition used, and the 30.06 AP M2 required proof velocities.

4. ELA TEST METHOD

The short annual test programme consists of a small number of plates, from which three separate results are acquired. For the ELA, a V_{50} across the plates is achieved using 4, 6 or 8 shots. This value is compared with the values from previous years. From the same shot data, it is expected that there will be a number of what can be considered to be proof shots, to prove that the plate still meets the NIJ-0101.04 level IV proof requirement. Finally, the user will probably never come up against a 30.06 AP M2 bullet, and so to provide them with some real-world confidence, one of the plates will have a relevant threat used to test them. This is in the form of three factory-charge 7.62 x 39 mm PS ball fired into it in a triangular pattern around the original 30.06 AP M2 centre shot.

In an ideal world the ELA would be conducted each year from the original manufacture date. However, the requirement to understand how an armour performs once it is out of warranty, only really becomes an issue in the minds of the user, once it is actually out of warranty, and in the case of this particular user, several years after it is out of warranty.

The testing was conducted in such a manner as to achieve three types of test results from the same series of plates:

1. Proof Test in the spirit of NIJ-0101.04
2. Extended Life Analysis (ELA) by V_{50}
3. Realistic Threat Proof Test

4.1 NIJ-0101.04 Proof Tests – Level IV Armour Plate

Any plate for which the impact velocity was within the proof velocity tolerance of 838 ± 9 m/s could be used as proof shots, whether they produce a partial penetration (PP) or a complete penetration (CP). Additionally, and in this case significantly more usefully, any shot whose velocity was greater than 847 m/s, for which the outcome was a partial penetration, could be included as a valid proof shot.

4.2 Extended Life Analysis V_{50}

The Extended Life Analysis V_{50} test consists of a single shot of the 30.06 AP M2 on each of the sample number of plates at velocities elevated above the required proof velocity, with the aim of achieving a 4-shot, 6-shot or 8-shot V_{50}, which can then be used for comparison with values from previous years. This then constitutes the Extended Life Analysis by V_{50}.

4.3 7.62 x 39 mm PS Ball

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The most prolific, and hence realistic, threat in the theatre of operation of this user would be a Kalashnikov AK47 firing 7.62 x 39 mm PS ball. Therefore, to add some real-world confidence for the user, one of the plates which has already been impacted with a single 30.06 AP M2, is impacted with a further 3 shots of 7.62 x 39 mm PS ball, fired as full-charge factory rounds from a proof barrel.

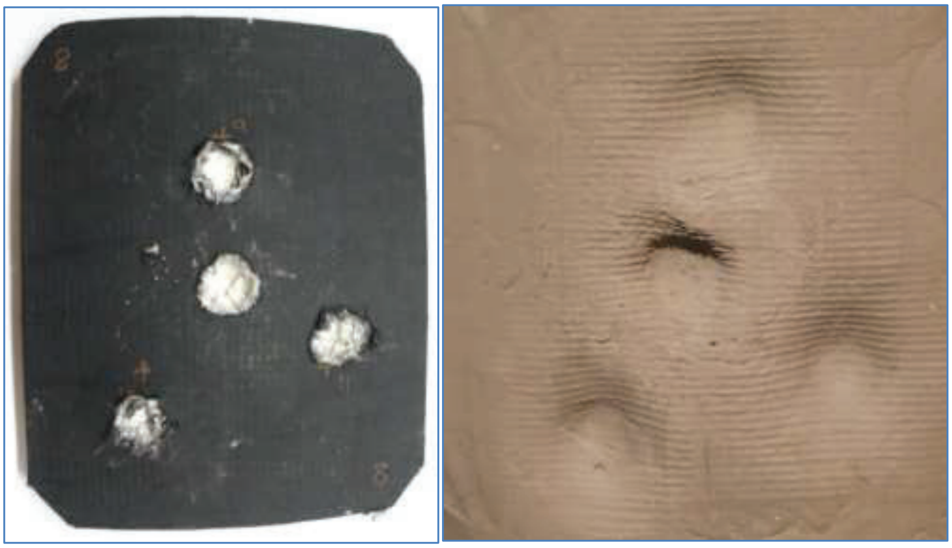

Figure 1. Plate with single shot of 30.06 AP M2 and 3 shots of 7.62 x 39 mm PS ball (left) and associated Plastilina backing with back-face signatures (right)

4.4 Test Method and Configuration

Each armour plate was mounted on a conditioned and calibrated box of Roma Plastilina Number 1.

The ammunition was charge-adjusted for each shot and fired from an appropriate proof barrel, mounted to a universal proof housing. The velocity was measured by optical sky-screens. The general trial configuration is as shown in Figure 2 below:

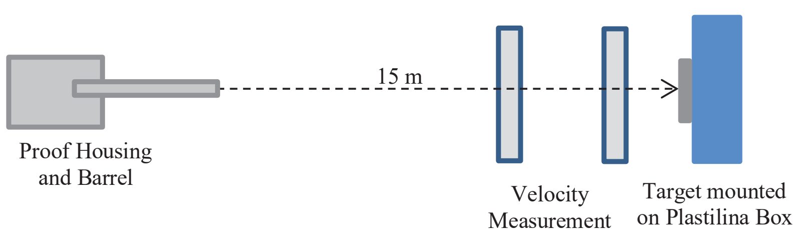

Figure 2. Plan View of General Trial Configuration

5. PLATE CONSTRUCTION

The ceramic-faced plates in this study have the advantage of being a very robust design. One of the first batch of plates delivered arrived without its black textile cover and hence it was easier to determine the construction of the plate. As previously stated, it is a robust design consisting of a thick (approximately 8 mm) alumina monolithic tile backed with a 9 mm glass-reinforced plastic (GRP) backing and all wrapped in GRP as a spall layer.

Figure 3. Example of Armour Plate without Black Nylon Cover

6. TEST RESULTS

6.1 Year 1 Test Results

The results of the Year 1 tests were not ideal, as despite very specific instructions, the user was not particularly careful about which plates they shipped for testing, and it turned out that there were 6 of one batch, 2 of another batch, a single plate of similar construction, and a single plate of a totally different geometry.

These constructions are outlined in Table 1 below:

Table 1. Construction of Level IV Armour Plates

Plate No	***Date of Manufacture***	***Construction***	***Plate Mass (kg)***
1	7/08	single curve – 8 mm alumina / 9 mm GRP	3.876
2	7/08	single curve – 8 mm alumina / 9 mm GRP	4.041
3	7/08	single curve – 8 mm alumina / 9 mm GRP	4.010
4	7/08	single curve – 8 mm alumina / 9 mm GRP	4.205
5	7/08	single curve – 8 mm alumina / 9 mm GRP	4.211
6	7/08	single curve – 8 mm alumina / 9 mm GRP	4.147
7	3/06	single curve – 9 mm alumina / 4.5 mm backing	3.825
8	3/06	single curve – 9 mm alumina / 4.5 mm backing	3.524
9	9/06	single curve – 10 mm alumina / 4 mm backing	3.880
10	3/06	flat – 9 mm alumina / 5 mm backing	3.861

6.1.1 NIJ-0101.04 Proof Tests – Level IV Armour Plate

For these 10 plates, a single shot of 30.06 AP M2 was fired centrally, at velocities at, or above, the required proof velocity. These velocities and the outcome are shown in Table 2. As the same shots are used for both the V_{50} calculation and the proof shots, many of the partial penetration proof shots are at velocities considerably higher than the requirements of the NIJ standard.

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Table 2. NIJ-0101.04 Proof Results for Level IV Armour Plate

Plate No	*Ammunition*	*Shot No*	*Bullet Mass (g)*	*Velocity (m/s)*	*Outcome (CP/PP)*	*BFS (mm)*
1	30.06 AP M2	A1	10.6	835	PP	30.8
2		A2	10.6	874	PP	19.1
5		A5	10.6	878	PP	32.1
6		A6	10.6	887	PP	34.8
7		A7	10.6	853	PP	33.8
8		A8	10.6	867	CP	n/a
9		A9	10.6	840	PP	28.7
10		A10	10.6	841	PP	36.7

Plate numbers 3 and 4 were not used as proof shots as they produced complete penetrations, which were used in the V_{50} component of the test.

6.1.2 Extended Life Analysis V_{50} - Level IV Armour Plate

The Extended Life Analysis V_{50} was conducted on the six plates, which were manufactured in July 2008. The results are shown in Table 3 below:

Table 3. Extended Life Analysis Results for Level IV Armour Plate

Plate No	*Shot No*	*Bullet Mass (g)*	*Velocity (m/s)*	*Outcome (CP/PP)*	*BFS (mm)*	*Used for V_{50} (Y/N)*
1	A1	10.6	835	PP	30.8	N
2	A2	10.6	874	PP	19.1	N
3	A3	10.6	905	**CP**	n/a	Y
4	A4	10.6	889	**CP**	n/a	Y
5	A5	10.6	878	**PP**	32.1	Y
6	A6	10.6	887	**PP**	34.8	Y

Due to the limited number of plates of a single construction available, it was only possible to produce a 4-shot V_{50}. The 4-shot V_{50} achieved was **890 m/s** within a spread of 26 m/s, which is somewhat wider than would be ideal. This value may now be used as the basis for future extended life analysis tests.

6.1.3 7.62 x 39 mm PS Ball

Plate 6 was chosen for the additional 3 shots of 7.62 x 39 mm PS ball. The results of these shots are shown in Table 4.

Table 4. 7.62 x 39 mm PS ball (Factory 04) Proof Results for Level IV Armour Plate

Plate No	*Ammunition*	*Shot No*	*Bullet Mass (g)*	*Velocity (m/s)*	*Outcome (CP/PP)*	*BFS (mm)*
6	7.62 x 39 mm PS ball (04 66)	A12	8.0	723	PP	8.3
6		A13	8.0	726	PP	10.2
6		A14	8.0	717	PP	9.5

6.1.4 Conclusion of Year 1 Results

From the above results, obtained with a non-ideal mix of submitted plates, it was determined that for future years a quantity of 8 plates should be sufficient to achieve both the required V_{50} and suitably high proof shot velocities. Plates 7 and 8 would indicate a marginal proof shot pass, with that construction. Plates 9 and 10 achieved singe shot passes of the proof shot, for their respective constructions, although there is insufficient shot data to draw conclusions with any confidence.

6.2 Year 2 Results

This test was a much more controlled test. All 8 plates shipped were of the same batch, and hence the same construction, which was the same as the batch of 6 plates from Year 1. For Year 2, the construction and mass of the individual plates is as per the Table 5:

Table 5. Construction of Level IV Armour Plates

Plate No	*Date of Manufacture*	*Construction*	*Plate Mass (kg)*
1	07/08	single curve – 8 mm alumina / 9 mm GRP	4.065
2	07/08	single curve – 8 mm alumina / 9 mm GRP	4.121
3	07/08	single curve – 8 mm alumina / 9 mm GRP	4.172
4	07/08	single curve – 8 mm alumina / 9 mm GRP	4.085
5	07/08	single curve – 8 mm alumina / 9 mm GRP	3.717
6	07/08	single curve – 8 mm alumina / 9 mm GRP	3.946
7	07/08	single curve – 8 mm alumina / 9 mm GRP	4.092
8	07/08	single curve – 8 mm alumina / 9 mm GRP	3.994

6.2.1 NIJ-0101.04 Proof Tests – Level IV Armour Plate

For these 8 plates, a single shot of 30.06 AP M2 was fired at each at velocities at, or above, the required proof velocity. Those velocities considered suitable as proof shots are shown in Table 6 below:

Table 6. NIJ-0101.04 Proof Results for Level IV Armour Plate

Plate No	*Ammunition*	*Shot No*	*Bullet Mass (g)*	*Velocity (m/s)*	*Outcome (CP/PP)*	*BFS (mm)*
1	30.06 AP M2	1	10.6	901	PP	33.1
3		3	10.6	900	PP	25.7
4		4	10.6	906	PP	29.6
6		6	10.6	910	PP	36.9
8		8	10.6	910	PP	26.8

Plate numbers 2, 5 and 7 were not used as proof shots as they produced complete penetrations, which were used in the V_{50} component of the test.

6.2.2 Extended Life Analysis V_{50} - Level IV Armour Plate

The Extended Life Analysis was conducted on eight plates, with the results of six plates used to achieve a 6-shot V_{50}. The full set of 30.06 shot results are shown in Table 7 below.

Table 7. Extended Life Analysis Results for Level IV Armour Plate

Plate No	*Shot No*	*Bullet Mass (g)*	*Velocity (m/s)*	*Outcome (CP/PP)*	*BFS (mm)*	*Used for V_{50} (Y/N)*
1	1	10.6	901	PP	33.1	N
2	2	10.6	921	**CP**	n/a	Y
3	3	10.6	900	PP	25.7	N
4	4	10.6	906	**PP**	29.6	Y
5	5	10.6	917	**CP**	n/a	Y
6	6	10.6	910	**PP**	36.9	Y

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7	7	10.6	914	**CP**	n/a	Y
8	8	10.6	910	**PP**	26.8	Y

The 6-shot V_{50} achieved was **913 m/s** within a velocity spread of 15 m/s. This value compares well with the March 2021 value of 890 m/s, and both values may now be used as the basis for future extended life analysis tests.

6.2.3 7.62 x 39 mm PS Ball

Plate 8 also had an additional 3 shots of factory charge 7.62 x 39 mm PS ball fired into it. The results of these shots are shown in Table 8.

Table 8. 7.62 x 39 mm PS ball (Factory 04) Proof Results for Level IV Armour Plate

Plate No	***Ammunition***	***Shot No***	***Bullet Mass (g)***	***Velocity (m/s)***	***Outcome (CP/PP)***	***BFS (mm)***
8	7.62 x 39 mm PS ball (04 66)	9	8.0	724	PP	15.8
8		10	8.0	736	PP	18.9
8		11	8.0	730	PP	17.6

6.3 NIJ-0101.04 Proof Tests over 2 Years

6.3.1 Year 1 Proof Results

Four shots above the proof velocity tolerance of 838 ± 9 m/s produced partial penetrations. The only complete penetrations were at 867 m/s and above. Therefore, there are no proof test failures of the armour plates tested at this time.

6.3.2 Year 2 Proof Results

Five shots above the proof velocity tolerance of 838 ± 9 m/s produced partial penetrations. The only complete penetrations were at 914 m/s and above. Therefore, there are no proof test failures of the armour plates tested at this time.

6.4 Extended Life Analysis (ELA) by V_{50} over 2 Years

6.4.1 Year 1 V_{50} Results

From the eight plates supplied, a V_{50} was obtained of 890 m/s, within a spread of 26 m/s. This value may be used as a basis for Extended Life Analysis in future years, as a means to extend the in-service life of the armour.

6.4.2 Year 2 V_{50} Results

From the eight plates supplied, a V_{50} was obtained of 913 m/s, within a spread of 15 m/s. This value, combined with the March 2021 result (890 m/s), may be used as a basis for Extended Life Analysis in future years, as a means to extend the in-service life of the armour.

6.5 7.62 x 39 mm PS Ball Results over 2 Years

6.5.1 Year 1 V_{50} Realistic Threat Results

The three additional shots of the 7.62 x 39 mm PS ball on plate 6, at velocities of 717 m/s and above, were easily defeated by the armour, leaving low back-face signatures.

6.5.2 Year 2 V_{50} Realistic Threat Results

The three additional shots of the 7.62 x 39 mm PS ball on plate 8, at velocities of 724 m/s and above, were easily defeated by the armour, leaving low back-face signatures.

7. DISCUSSION

In an ideal world, ELA should be considered as soon as an armour system is accepted for service, and the V_{50} should be conducted on the first production batch, as part of the initial acceptance testing. This would set the baseline performance value. Up until now this has not usually been done with ceramic armour plates, although it is common with items such as fragmentation vests, which are tested using fragment simulating projectiles (FSPs) and a V_{50} anyway.

For ceramic armour plates, accepting that the ELA is not started until the end of the warranty period, at the earliest, and that there is no baseline measurement to use, the 1st year should be considered as a learning experience, for both users and testers. Any V_{50} values obtained during the first year should be considered as indicative and should be used to inform the starting place for consecutive years.

ELA is, by its very nature, a destructive test, meaning that the inventory of armour plates diminishes by a number of plates each year. The programme is designed in such a way as to keep this annual plate reduction to a bare minimum. However, there will come a time when this testing is no longer viable, as the remaining number of plates will be too low to meet the requirements of the user. The number of plates requested for the ELA test is therefore kept to number, that many people may consider too low to obtain statistically significant results. For Year 1 this was 10 plates, which although compromised (due to the mixed batch), was deemed just adequate. For Year 2 it was deemed possible to reduce the number of plates required to 8 items. It is probably not possible to reduce that number any further, for a number of reasons. Predominantly, is the fact that these plates undergo a significant journey between the user base and the test house (with some challenging border customs to negotiate), so it seems prudent to remain with a sample size of 8. If this was reduced to 6, for example, any extras required due to issues during testing, would take a long time to arrive. This low number does mean that the 'proof' outcome is based upon much fewer shots than would normally be statistically required. However, due to the safety margin which still appears to exist with these plates, combined with the encouraging V_{50} results, this compromise is deemed acceptable, in this case. This acceptability is further increased by the fact that the realistic threat to the users is significantly lower than the armour specification.

It should be noted that the above discussion relates to these particular plates and the scenario in which they are used. In other cases, there could be some very good arguments to increase the sample size for testing. This could be, for example, if the first ELA test indicates that the plates are borderline in their performance. In such a case a larger sample size would provide the user with greater confidence, especially for the proof aspect of the tests. There may also be a scenario in which the initial specification of the plate is now borderline versus the current threat assessment. There could also be a situation where the inventory stock of plates includes many plates in excess to the operational requirement for numbers, and hence there is a greater resource for testing to call upon each year.

8. LESSONS LEARNT

For the first year, where the baseline is being set, the requirement for plate numbers is higher than it should be for subsequent years. The aim is to keep the number of plates used each time to a bare minimum, so as not to unnecessarily reduce the stock more than it needs to be. From the experience of this study, this is probably 8 plates. Ideally, plates would have an initial V_{50} test conducted when first manufactured, to provide a real baseline performance value. This would then allow the first year of ELA to be conducted with only 8 plates. In the absence of this initial production acceptance baseline, Year 1 of the ELA is considered to be that baseline, and hence the results for Year 1 should be considered indicative and used to inform Year 2 onwards.

It is critical that the user / supplier of the plates is meticulous in ensuring that the plates are from the same batch, and that there is evidence to prove it. In this study, the Year 1 plate submission was somewhat erratic, making it impossible to obtain a V_{50} with more than four shots from the same batch.

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9. SUMMARY

When body armour upgrade plates exceed their warranty period, there is often a desire to gain confidence that they still perform as they should. ELA is a method, albeit a destructive one, which allows the year-on-year performance of the armour to be monitored in a numerical way.

The method of ELA used for this study allows for three different results: proof shots, V_{50} and reality check, from the same batch of 8 – 10 plates. V_{50} and proof values used will be the same shots in many cases, thus reducing the need for extra plates, and hence a greater reduction in the inventory of plates available to the user.

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Glossary

AP	armour-piercing
ELA	Extended Life Analysis
NIJ	National Institute of Justice (USA)
V_{50}	the velocity at which, with a specified projectile and a specified armour system, the probability of perforation of 0.5

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