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New Zealand Police

CREWE HOMICIDE INVESTIGATION REVIEW

'A Multivariate Approach to Discriminating Between Batches of Cartridge Cases Using Design Changes in the Headstamp'

APPENDIX 9

Appendix 9

'A Multivariate Approach to Discriminating Between Batches of Cartridge Cases Using Design Changes in the Headstamp' (2011), by Christopher PRICE (M.Sc Thesis)

A MULTIVARIATE APPROACH TO DISCRIMINATING BETWEEN BATCHES OF CARTRIDGE CASES USING DESIGN CHANGES IN THE HEADSTAMP

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A thesis submitted in fulfilment of the requirements for the degree of Master of Science in Forensic Science

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ABSTRACT

A study was conducted to determine whether subtle changes could be discerned in the ICI headstamps impressed into .22 Long Rifle cartridges produced over time by the Colonial Ammunition Company, in order to define a specific period of manufacture.

A large number of boxes of relevant ammunition were obtained and 117 of these were selected for sampling. An optimised set up was used to photograph the headstamps and the resultant images were processed for data collection.

The data was collected in the form of Cartesian coordinates, with 22 coordinates collected from each headstamp. The coordinate data was used in a brief exploration of the data, after which the coordinates were used to calculate data transformations providing measurements of the various parameters of the headstamps. The various data transformations were assessed and a selection of these were used in the statistical analysis of the headstamps.

The ability to predict the batch source of a headstamp was assessed using Linear Discriminate Analysis. The accuracy of the batch predictions were measured using a cross-validation method which showed the predictions for the dry-primed cartridges were within five to six months (on average) of the true production date and the predictions for the wet-primed cartridges were within two months (on average) of the true production date.

A blind study was conducted which showed that the classification model was very accurate.

An exhibit from a historic murder in New Zealand was also examined to predict its production period. Its assignation is discussed in detail with reference to the relevance of this to the murder case.

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1 - INTRODUCTION

During the prosecution of Mr Arthur Allan Thomas for the Crewe murders (1970), an important element of the judicial proceedings involved a consideration of the link between the fatal bullets recovered from the victims and a cartridge case which was recovered from the crime scene.

In order to determine the production period for the questioned cartridge case, an analysis was conducted of the design features of the headstamp. There was considerable debate about how the statistical analysis should be performed and further debate on the findings from various analyses. However, the general conclusion suggested that no link could be provided between the fatal bullets and the crime scene cartridge case.

For this project it was proposed to further investigate the design features of the headstamp in order to determine whether or not it was possible to define a more specific time period of manufacture.

1.1 THE CREWE MURDERS

1.1.1 Background

The last time Mr David Harvey Crewe and Mrs Jeanette Lenore Crewe were seen alive was at 4pm on 17th June 1970 as they were driving home from a stock sale in Bombay [1]. Five days later a bloodied crime scene was discovered at their house in Pukekawa [2, p13]. The bodies of Mr and Mrs Crewe were not found at the scene, although it seemed likely from the analysis of extensive bloodstains and a small amount of brain tissue found, that both were dead [2, p14]. The Crewe's 18-month old daughter was found inside the house, alive but obviously distressed. Upon discovery of the crime scene, a murder investigation was launched by the New Zealand Police.

An extensive search of the house and surrounding area yielded no clues as to how Mr and Mrs Crewe were killed [2, p14]. On 16th August 1970, fifty-five days after the discovery of the bloodstained house, Mrs Crewe's body was found in the Waikato river. Mrs Crewe had received a gunshot to the head. This finding resulted in another unsuccessful search of the house and surrounding area, with a particular focus of finding a fired cartridge case. The bullet fragments recovered from the head of Mrs Crewe were .22 calibre. One of the recovered bullet fragments contained the base of the bullet with the number 8 embossed on it. This particular fragment would become important at a later date of the investigation and subsequent prosecution. The recovered bullet fragments were sent to the Department of Scientific and Industrial Research (DSIR) for comparison with bullets test-fired from .22 calibre rifles collected from relatives and associates of Mr and Mrs Crewe, and from residents that lived within a five mile radius of their farm. One of the rifles collected belonged to Mr Thomas as the Police had established some association between Mrs Crewe and Mr Thomas in earlier years. Preliminary findings by DSIR on 19th August concluded that Mr Thomas's rifle and a rifle belonging to the Eyre family (neighbours of the Crewes), could not be excluded as having fired the fatal bullet.

On 16th September 1970, eighty-six days after the discovery of the bloodstained house, Mr Crewe's body was found in the Waikato river [2, p15]. Mr Crewe had suffered the same fate as his wife [2, p14]. The fragments of the bullet recovered from Mr Crewe were more severely damaged than those recovered from Mrs Crewe and therefore were of less assistance in identifying the rifle from which the bullet had been fired. However, the remnants of a number 8 was able to be identified on a fragment containing the base of the bullet.

Sometime between the 13th and 16th of October 1970, scientists at DSIR confirmed the preliminary findings that of the 64 rifles examined, only the Thomas rifle and the Eyre rifle could not be excluded as having fired the fatal bullets [2, p14]. A positive identification was not possible due to the damaged state of the projectiles. At this point the investigation into the murders of Mr and Mrs Crewe was focused towards Mr Thomas. An uncounted box of .22 ammunition was recovered from Mr Thomas's farm on 13th October 1970 by Detective Johnston. Later that day, the Police executed a reconstruction of how Mr and Mrs Crewe may have been murdered [2, p15]. Around this time (between 30th September and 27th October) the neighbours of the Crewes, Mr and Mrs Priest, recalled hearing two shots fired from the direction of the Crewe farm. These shots had reportedly been fired by Detective Inspector Hutton (the officer in charge of the case) and Detective Johnston [2, p15].

A third and final search of the crime scene was ordered on 27th October 1970 with particular focus on an area of garden near the back door of the house [2, p19]. The reason behind this search was based on the assumption that if the killings had been carried out in the manner of the Police reconstruction on 13th October, an empty cartridge case may have been ejected into the garden or surrounding area during reloading. Although this garden had already been searched twice, on this occasion a fired .22 cartridge case was found within two hours of beginning the search [2, p20].

The firing pin impression on the fired cartridge case was examined at DSIR and it was determined that the cartridge case had been fired in Mr Thomas's rifle and no other rifle [2, p17].

On 11th November 1970, Mr Thomas was arrested and charged with the murders of Mr and Mrs Crewe [2, p15]. The recovered cartridge case, which at trial became "exhibit 350", became the premier piece of evidence used in the prosecution. The first trial took place between 15th February and 2nd March 1971, with the jury reaching the verdict that Mr Thomas was guilty of murder on both charges [2, p16].

During the next two years Mr Thomas remained in prison whilst various petitions were submitted to the Court of Appeal seeking a retrial. On 26th February 1973 the Court of Appeal ordered a second trial of Mr Thomas which took place between 26th March and 16th April 1973 [2, p16], with the jury reaching the same verdict as in the first trial. Mr Thomas was again convicted of murder on both counts and sentenced to life imprisonment. Supporters of Mr Thomas persisted with several more appeals lodged to the Court of Appeal and petitions lodged to the Governor-General, but these were to no avail. The main issue addressed in these appeals revolved around a question which had been raised at the end of the second trial. This concerned whether the fired cartridge case (exhibit 350) could have had any connection with the fatal bullets. This issue was further pursued by Dr Thomas Sprott and Mr Pat Booth.

1.1.2 Exhibit 350 and the Fatal Bullets

Exhibit 350 was a .22 Long Rifle rimfire (.22LR) cartridge case [2]. The cartridge case was made of brass and had been primed by the "dry priming" method (see 2.3.1). The headstamp on exhibit 350 had the letters "ICI" in sans-serif font (Figure 1.1) [2]. This headstamp identified the cartridge case as being produced by Imperial Chemical Industries in Australia (ICI Australia) [3]. The number 8 seen on the base of the fatal bullets identified them as being "Pattern 8" bullets produced by Colonial Ammunition Company (CAC) in Auckland, New Zealand (see 2.6.3.1) [2, p23]. CAC produced .22LR cartridges in New Zealand using cartridge cases that had been manufactured by ICI Australia [3]. Therefore, exhibit 350 was considered consistent with the fatal bullets. However, on 10th April 1973, during the last week of Mr Thomas's second trial, a matchbox containing a number of cartridges and a letter was delivered to Dr Sprott [2, p30].

The letter and matchbox had been sent by Mr J. B. Ritchie, a sports goods dealer and former member of the New Zealand Police from Dannevirke. The letter addressed the fact that only certain types of cartridge cases bearing the sans-serif-ICI headstamp were loaded with the type of bullet recovered from the heads of Mr and Mrs Crewe. More specifically, only cartridge cases bearing a significantly smaller sans-serif-ICI headstamp than that seen on exhibit 350, were found loaded with Pattern 8 bullets. The bullets found loaded in cartridge cases bearing headstamps like that seen on exhibit 350 were a later style of bullet known as Pattern 18 or Pattern 19 (see 2.6.3.2). The significance of this finding was that Pattern 8 and Pattern 18/19 bullets had distinct differences, one of these being that Pattern 18/19 bullets did not have the number 8 embossed on their base [2, p24]. This suggested that exhibit 350 could not have been loaded with a Pattern 8 bullet and therefore this cartridge case was not connected to the fatal bullets.

Figure 1.1: Photograph of exhibit 350 showing the sans-serif-ICI headstamp.

Immediately after this discovery, Dr Sprott started analysing various cartridge cases bearing the "ICI" headstamp [2, p30]. By the evening of 12th of April, Dr Sprott had located and examined around 600 cartridges and had discovered the headstamps found on these cartridges could be broadly fitted into four categories which he labelled Categories 1, 2, 3 and 4 [4]. Categories 1 and 2 (Figure 1.2) were irrelevant to the investigation as these headstamps were in a different design and font to that on exhibit 350. The headstamps for Categories 3 and 4 were both sans-serif font, however differences existed in the height of the letters in the headstamp, with Category 4 headstamps having substantially larger lettering (Figure 2.13). Upon analysis of the bullets loaded into these cartridges, Dr Sprott discovered that Category 1, 2 and 3 cartridges were always loaded with a Pattern 8 bullet and the Category 4 cartridges invariably contained either a Pattern 18 or Pattern 19 bullet. Dr Sprott analysed exhibit 350, which he determined fell within Category 4. This evidence was presented at the end of the second trial. This evidence was rebutted and the jury were insufficiently persuaded by the findings, which resulted in the second conviction of Mr Thomas.

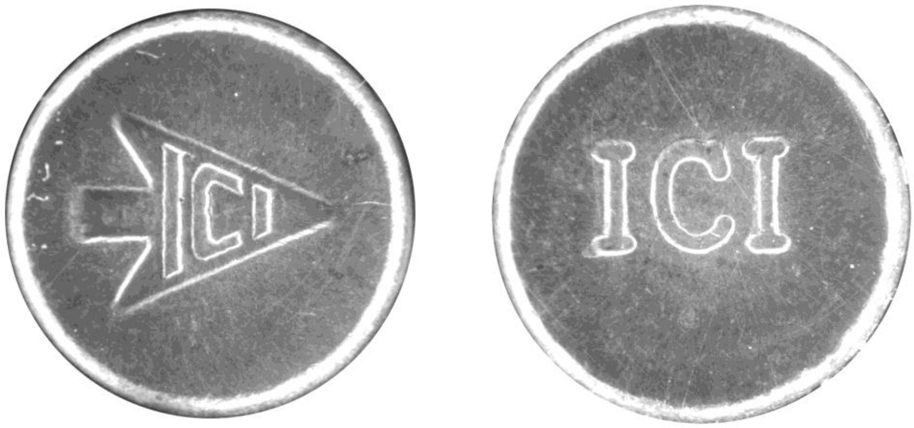


Figure 1.2: Dr Sprott's Category 1 headstamp (left) and Dr Sprott's Category 2 headstamp (right) [3].

Following the second conviction of Mr Thomas, Dr Sprott continued his research and discovered another two categories of headstamp in addition to his original four [4]. One of these was a sub-category of Category 3 with slightly smaller lettering. He distinguished these as Categories 3a and 3b [2, p31]. The other new category was similar to Category 4, however the overall width of the "ICI" lettering was significantly larger. This category was labelled "Wide-I" (Figure 2.13) [4]. Cartridges bearing the Wide-I headstamp appeared to contain either Pattern 8, Pattern 18 or Pattern 19 bullets. The Wide-I headstamp appeared to have been used periodically between the change-over from Category 3a and 3b headstamps to Category 4 headstamps [2].

From analysis of the production records from CAC in New Zealand, Dr Sprott discovered that Pattern 8 bullets were produced in large quantities between 1948 and 1963, with the last batch being loaded on 8th November 1963 [2, 5]. This date would turn out to be very significant.

In late 1973, Dr Sprott visited the ICI factory in Australia to gain a thorough understanding of the processes behind cartridge case manufacture [4]. It was the practice of ICI Australia to retain a sample of completed cartridge cases from each batch that was produced, for testing and subsequent examination. Although the samples only dated back to 18th September 1963, the results from applying Dr Sprott's analysis to these samples showed that: samples retained from

18th September 1963 till 26th February 1964 were of Wide-I category; Category 4 cartridge cases were first encountered on samples dated 4th March 1964 and thereafter until August 1964 the samples were either Category 4, Wide-I, or a mixture of these; from 23rd September 1964 onwards, all the cartridges were Category 4. The assumption was made that the cartridge cases received by CAC in New Zealand followed the same pattern, albeit slightly delayed due to the time taken to ship the cases to New Zealand. From further analysis of the shipping records, Dr Sprott found that the shipment containing the first examples of the Category 4 cartridges arrived in New Zealand on 28th April 1964. This meant that cartridge cases bearing the Category 4 headstamp were not used in New Zealand until at least five months after the cessation of the use of Pattern 8 bullets. Dr Sprott concluded that exhibit 350, a Category 4 cartridge, could not have been loaded with a Pattern 8 bullet and therefore could not have been linked to the fatal bullets. This led to assertions that exhibit 350 had been planted by the Police, eventually resulting in the pardon of Mr Thomas in 1979 by the Prime Minister, the Right Honourable Robert Muldoon [2, p17]. A Royal Commission of Inquiry into the circumstances of the convictions of Arthur Thomas for the murders of Mr and Mrs Crewe (1980 Royal Commission of Inquiry) involved a thorough investigation of this matter [2].

1.1.3 The 1980 Royal Commission of Inquiry

At the Royal Commission of Inquiry there was significant debate as to the significance of the slight changes seen in the headstamps. This was resolved by a graphical demonstration which showed the difference between the various categories of headstamp [2, p42]. This concurred with Dr Sprott's previous findings that the headstamp on exhibit 350 was of a type produced after the cessation of loading Pattern 8 bullets [2].

Other theories were proposed by the prosecution in order to provide an explanation of how exhibit 350 could have been linked with the murders. These theories included the possibility of a Pattern 18/19 bullet being stamped with an 8 on its base, or that exhibit 350 could have been an "empty case in the chamber" of Mr Thomas's rifle which was ejected prior to loading cartridges containing the fatal bullets [2]. For more information regarding these theories refer to the "Report of the Royal Commission to Inquire into the Circumstances of the Convictions of Arthur Allan Thomas for the Murders of David Harvey Crewe and Jeanette Lenore Crewe" [2].

1.1.4 Headstamp Analysis at the Second Referral and 1980 Royal Commission of Inquiry

Evidence which disputed Dr Sprott's headstamp categorization was given by Mr Ian McDonald at the Second Referral to the Court of Appeal on behalf of the prosecution. Mr McDonald was the Dominion Analyst and Director of the Chemistry Division of DSIR [2, p31]. Mr McDonald had examined approximately 150 headstamps and made various measurements concerning the dimensions of the letters [2, p36]. The measurements were made using a microscope with the distances measured from the relevant edges of the lettering within the headstamps [4]. In order to present an easily understandable illustration of his measurements, he plotted certain measurements against each other [2, p38]. One of the graphs showing Mr McDonald's bivariate analysis is shown in Figure 1.3. This addressed the "overall width of the letters I-C-I" plotted against the "sum of the letter heights I+C+I" [2, p39].

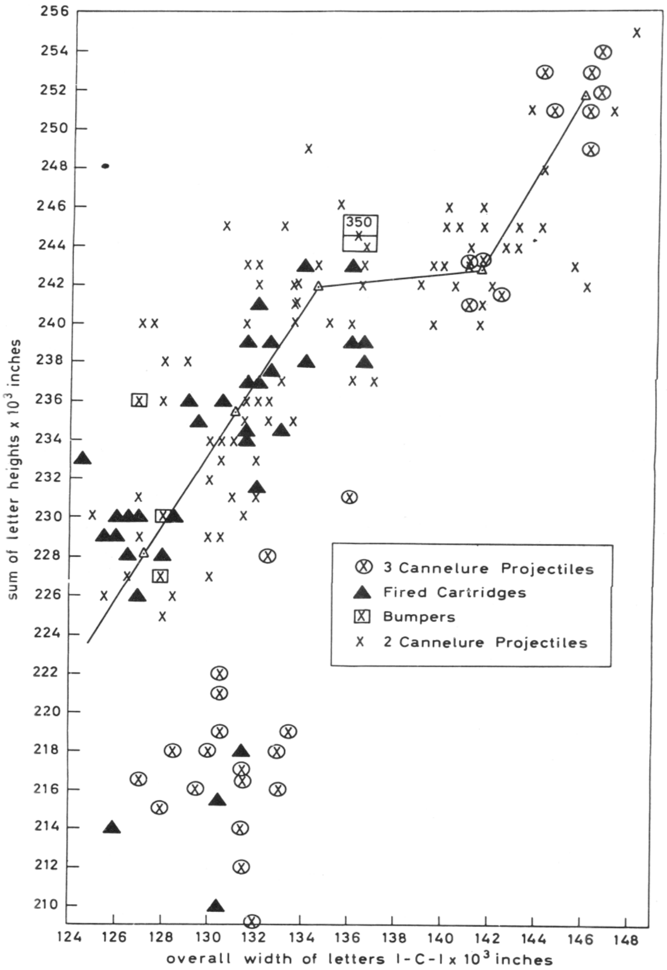


Figure 1.3: Graph of Mr McDonald's measurements, "overall width of the letters I-C-I" versus "sum of letter heights I+C+I". [2, p39].

The conclusion drawn from this graph was that the headstamps did not fall into the three discernable categories as Dr Sprott had proposed. Instead there was little correlation evident between the headstamps on different cartridge cases, as far as the measured parameters were concerned [4]. Mr McDonald also analysed the letter dimensions of exhibit 350 and included these in the graph. Exhibit 350 was seen as an outlier, however Mr McDonald conceded that it fell to the side of a grouping of a number of cartridge cases which Dr Sprott described as Category 4 [2, p38]. Other bivariate analyses performed by Mr McDonald were:

- I-C distance versus C-I distance.
- Width of left-hand letter “I” versus width of right-hand letter “I”.
- Height of letter “C” versus gap between horns of letter “C”.

The resulting graphs for the other analyses are not available but they were given to Dr Sprott during the 1980 Royal Commission of Inquiry [4]. Upon analysis of the graphs, Dr Sprott described them as a random scatter of points which at first examination would tend to indicate that there was little correlation between the various parameters analysed.

In rebuttal to Mr McDonald’s evidence, Dr Sprott pointed out that using a microscope to obtain precise measurements of the letters would be difficult due to irregularities of the edges of the letters [4]. Professor Mowbray, from the Engineering Department of the University of Auckland, was brought into the case by Dr Sprott to give an independent opinion of Mr McDonald’s evidence [2, p38]. Professor Mowbray appreciated the bivariate analyses conducted by Mr McDonald however he proposed that “one serious error” had been made during the analysis. Professor Mowbray explained that when making measurements, engineers always work with “skeletal” measurements, from centre line to centre line. Such measurements are “exact and absolute, without being subject to variables such as the width of the cutting tool, amount of wear on the cutting tool or wear on the bunter used to impress the headstamp”. He also stated that the letter “C” was usually drawn as an uncompleted “O”. Professor Mowbray had realised the possible significance of the “horn angle” of the “C”. The horn angle refers to the angle between the centre point of the “C” (or uncompleted “O”) and the end points of the horns of the “C”. By simple observation of the headstamps by the naked eye, the horns of the “C” can be seen to be much closer together in Category 4 headstamps than they are in Category 3 headstamps. Therefore, the horn angle would be smaller for Category 4 headstamps than it would for Category 3 headstamps. Calculation of the horn angle was done by Professor Mowbray using simple geometry. A diagram showing the skeletal lines of the letters and Professor Mowbray’s method of finding the horn angle is shown in Figure 1.4.

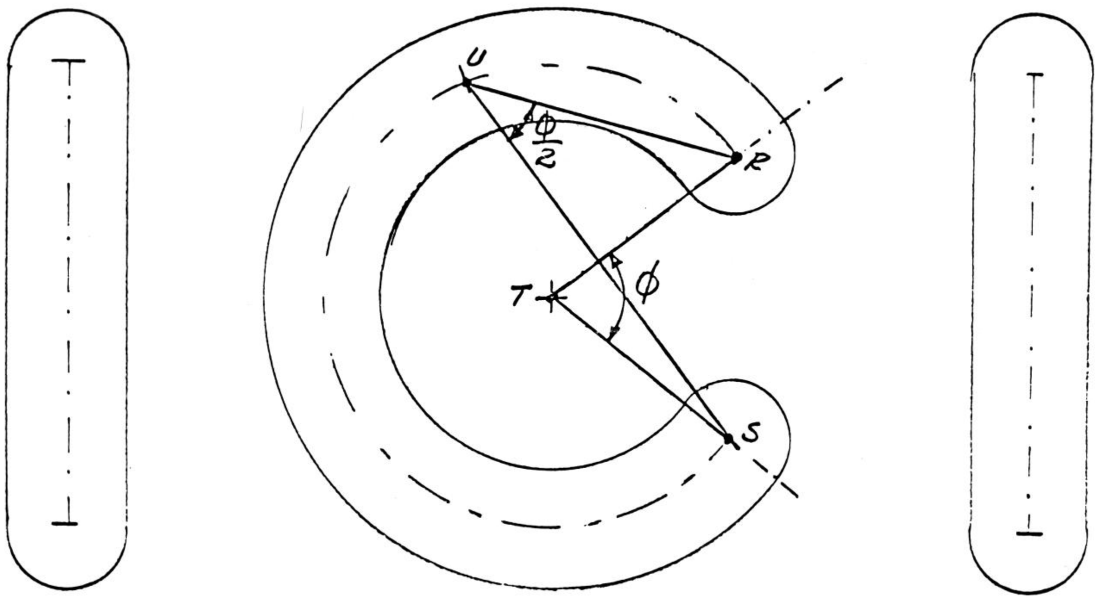


Figure 1.4: Schematic showing the sans-serif-ICI headstamp with skeletal lines added and Professor Mowbray's method of measuring the horn angle. [2, pg 41].

In calculating the horn angle, Professor Mowbray used the geometry principle that any angle subtended at any point drawn on the skeleton of the letter "C" by the horn centres R and S is half the angle subtended at the centre of the "C"(or incomplete O) by points R and S (Figure 1.4) [2, pg38].

Professor Mowbray and Dr Sprott obtained the cartridges which Mr McDonald had previously used for his analysis and applied their method of analysis to the headstamps using the skeletal measurements and the horn angle [4]. Professor Mowbray found the most useful parameters to be the horn angle and the overall skeletal width of the letters "ICI" in the headstamp [2, pg40]. When these two variables were plotted against each other in a graph (Figure 1.5), the results showed three distinct islands of headstamps separated by what Professor Mowbray called "wide open sea". Each island represented one of Dr Sprott's Categories. The same analysis was applied to exhibit 350 and this showed that it belonged in the middle of the Category 4 island.

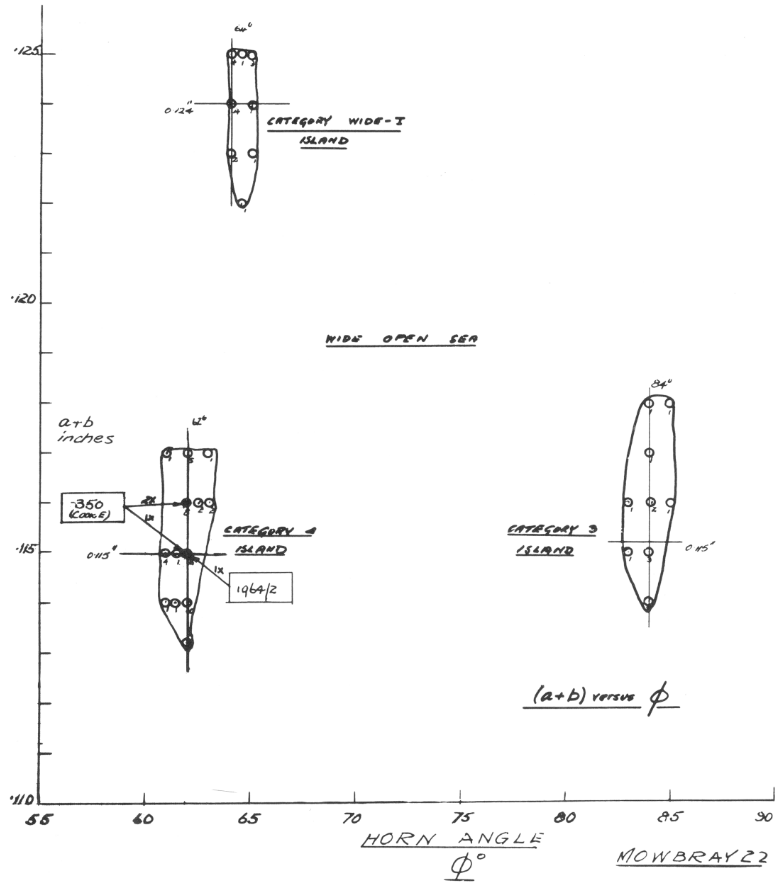


Figure 1.5: Dr Sprott and Professor Mowbray's graphical presentation of "horn angle" vs "skeletal width of the letters ICI" [2, p42].

This evidence, along with the finding that Category 4 headstamps were only used after the cessation of Pattern 8 bullet production, eventually led to the pardon of Mr Thomas for the murders of Mr and Mrs Crewe in 1979.

1.2 PURPOSE OF THIS THESIS

The analysis techniques used by Mr McDonald, Dr Sprott and Professor Mowbray to show variations and similarities between the headstamps were relatively unrefined compared to what is available today and their work was based on relatively few examples. These methods were performed in the late 1970s, when there were no personal computers. Mr McDonald's analysis was performed using a microscope method for the determination of the various parameters and this involved measuring from edge to edge of the incused letters of the headstamps [4]. The analysis performed by Dr Sprott and Professor Mowbray used enlarged photographs of the headstamps to measure the various parameters from the skeletal lines of the letters.

Understandably, the analysis of each headstamp would have been costly and time-consuming which enforced limitations on the number of headstamps that could be analysed. The result of this was multiple small-scale analyses of the variation in the headstamps. Since then, there have been substantial advancements in technology and the world has entered the digital age. One technological advancement has been the relative ease by which digital images can be immediately uploaded to a personal computer. By utilising the appropriate software the images can be easily and accurately analysed and relevant data collected. Large amounts of recorded data can be stored on computers and subjected to various sophisticated statistical analyses. In short, the technological progress has released the past constraint on data analysis, allowing researchers to engage in far more substantial studies [6, pg3].

The statistical methods used for the original analyses were quite undeveloped and lacked discriminating power. The statistical analyses involved simple bivariate analyses. However, it is likely that there are many variables within the headstamps which may have been useful in categorizing the headstamps more specifically. As one researcher stated “one is pushed to a conclusion that unless a problem is treated as a multivariate problem, it is treated superficially” [6, pg3].

Over the last 45 years a large number of statistical programmes have been developed which are capable of analysing data containing a very large number of variables (multivariate analysis). The substantial development of multivariate statistical methods has been largely spurred by the widespread applications of computers to process large, complex databases [6, pg4]. The statistical theory behind today’s multivariate techniques was developed well before the appearance of computers, however only when the computational power became available to perform complex calculations did the techniques existence become known outside the field of theoretical statistics. The continued technological developments in computing, particularly personal computers, has lead to the availability of statistical resources needed to address almost any sized multivariate problem. Comprehensive statistical packages can be easily obtained for personal computers as well as specialised programmes for all types of multivariate analysis.

Despite the relatively unsophisticated approach used by Professor Mowbray and Dr Sprott, it must be acknowledged that a significant finding was deduced from the analysis. However, it received considerable criticism from other participants, but this criticism was not accepted at the 1980 Royal Commission of Inquiry.

For this project it was proposed to perform a large-scale multivariate analysis of the sans-serif-ICI headstamp, over a wide manufacturing period, to investigate whether a more complex approach, utilising the advancements in computing and multivariate statistics, could add more information to that gained from the original working. The purpose behind this analysis was to determine whether or not the subtle changes in the class characteristics of the headstamps produced over time could be discerned and used to gain a more accurate picture of when these changes took place. The application of this study might allow a cartridge case of unknown origin to be analysed in order to determine the approximate date of manufacture.

Although this project only dealt with the subtle differences in class characteristics of the sans-serif-ICI headstamp, there are other headstamps which have also been shown to have class variants and there may be some application to these. During a court proceeding in New Zealand a headstamp from a cartridge case found at a crime scene was shown to have different class characteristics to the headstamps seen on cartridges within a box of ammunition found at a suspect's house [7]. From this information a defence scientist postulated that as the headstamp on the crime scene cartridge was different to that seen in the partial box of ammunition from the suspect's house, the crime scene cartridge could not have came from the suspect's box of ammunition. The headstamp of interest in this case was the "Rem" headstamp found on Remington .22LR cartridges. The scientist called by the prosecution explained that there was a range of class variants of the "Rem" headstamp that are often seen together in boxes of Remington .22LR ammunition. Figure 1.6 shows three class variants found in a single box of Remington .22LR ammunition.

Figure 1.6: Photographs of the class variants of the "Rem" headstamp.

When assessing the "Rem" class variants the main features to identify are the size and font of the lettering and the styling of the letters with particular regard to the upward flicks at the end of the "R" and the "m". Although the headstamp on the crime scene cartridge differed to that seen in the box of ammunition found at the suspect's house, this did not necessarily mean the cartridge did not come from that box of ammunition [7].

1.3 PREVIOUS BUNTER STUDIES

A number of previous studies have looked to link headstamps from different cartridge cases to a unique bunter. In order to understand the basis of this analysis it's important to have knowledge of the processes involved in bunter formation (see 2.4.1). A bunter is used to impress the headstamp into a cartridge case during cartridge case manufacture (see 2.2.6). There are two different methods used to produce bunters. The "hobbing" method of producing bunters was used by ICI Australia and this method utilises a hob, which has the depressed, reversed print of the desired bunter on its surface. The raised print on the bunter is formed by pressing the bunter against the hob in a hydraulic press. Bunters have traditionally been made using hobbing techniques, but now all the major ammunition manufacturers use Electrical Discharge Machining (EDM) to manufacture their bunters [8].

EDM removes metal from a work piece through a combination of vaporization and thermal erosion by using electrical discharges [8]. A dielectric fluid, usually an oil, is used to facilitate this process. The work piece and the electrode, which are oppositely charged, are brought within 10-100 micrometers of each other. The electrode is in the shape of the reversed negative of the required design on the bunter. The work piece is a soft tool blank which is formed into the bunter followed by hardening before use. Large voltage differences between the electrode and the work piece are generated by a direct current power supply. The voltage becomes sufficiently high so that the dielectric fluid in the gap between the electrode and the work piece becomes ionized and a spark between the work piece and the electrode ensues. The electrical discharge contains enough energy to melt and vaporize part of the work piece along with a portion of the electrode. The electrode is made up of a material with a higher melting point than the work piece therefore the erosion on the electrode is far less than the erosion on the work piece. The highly concentrated electrical energy is discharged along the path of least resistance, similar to how a lightning bolt strikes the highest conducting object on the ground. The path of least resistance for each electrical discharge depends upon the relative erosions of the electrode and the working surface, both of which are random processes. For this reason, the exact location of where the electrical discharge will strike the work piece is impossible to predict, leading to the production of microscopically unique bunters in each instance [9]. Further differences between bunters are produced by the state of wear on the electrode. Several studies have examined bunters made by EDM and have proven that each bunter produced has microscopic differences which can be seen on the bunters as well as in the impressions left by the bunters (i.e. in the headstamps) [9, 10, 11, 12, 13]. This has an application in forensic science as the headstamps on different cartridge cases can be shown to have been produced by the same bunter. The evidential value of performing such an analysis can be quite substantial. A hypothetical example follows; Assume an ammunition manufacturer produces 100,000 headstamps with a single bunter, this is 100,000 out of many millions of cartridges produced each year. A cartridge case is found at a scene and a box of the same branded ammunition is obtained from a suspect's house. Upon further analysis of the cartridges it is identified that the cartridge found at the scene and the cartridges found at the suspect's house have headstamps that have been produced from the same bunter. From this information an examiner can testify that the two matching cartridges have came from the same bunter and therefore could have come from the same box of ammunition or different boxes of ammunition containing matching cartridge case headstamps.

However, real life examples are invariably more complicated due to the use of multiple bunters at any one time at all of the major ammunition makers. All the cartridges produced by the different bunters share a common bin before priming, loading, packaging and distribution [14]. For this reason any box of ammunition can contain cartridges bearing any number of common headstamps that could have been produced from a number of different bunters. Similarly, when multiple shots are fired at a scene the fired cartridge cases left behind can have headstamps from a number of bunters.

Work has also been performed on monitoring how the toolmarks from bunters produced by EDM change as bunters become worn. Cartridges bearing headstamps from the same bunter were sampled from the start and the end of the bunter's production run [12]. It was shown that the bunter marks on these cartridge cases differed such that they could not be identified to each other. Therefore the conclusion was drawn that all bunters produced by EDM are microscopically unique and additionally the bunter marks produced from each bunter change as the bunter becomes worn.

With the relative abundance of scientific studies conducted on bunters produced by the EDM method, the lack of work done on bunters produced by hobbing is perhaps surprising. It has been shown that the headstamps from EDM-produced bunters show more microscopic differences than those of hobbing-produced bunters [11]. This suggests that the bunters produced by hobbing may be harder to distinguish in instances where the same hob is used to produce the bunter. A study has been conducted on the bunters used to impress the serial numbers on motor vehicle engines where the bunters were produced by hobbing [15]. Although this process is obviously different to impressing headstamps on cartridges, the underlying dynamics of the process remain the same. A hob was used to produce 1000 bunters and a selection of these were selected for comparison tests. Of the bunters selected, all were able to be discriminated using microscopic differences. Upon further analysis, the microscopic differences between the bunters were shown to be independent of the hobbing process. The microscopic differences arose from random grinding marks on the blanks, created prior to the blank being formed into a bunter. In considering the relevance of the findings of this study to the manufacture of bunters used to impress headstamps at ICI Australia, it is unknown if the tool blanks were subject to grinding prior to hobbing. However it is presumed that some form of tooling is likely to have been carried out. This suggests that each bunter produced by hobbing at ICI Australia could have produced unique headstamps when referring to microscopic detail.

Importantly, all of the mentioned studies used microscopic detail in the headstamps, or on the bunters, to distinguish between bunters. In instances where microscopic detail has been used, the class characteristics (style) of the bunters and impressed headstamps have been assumed to be the same. There have been no published studies in scientific literature that have looked to distinguish bunters and headstamps by class characteristics in order to distinguish between different time periods of production. A study such as this does not look to individualise each bunter, but rather focuses on when the design features of the hobs (and therefore bunters) changed. Although there have been no published studies on this, such studies were performed by Dr Sprott, Professor Mowbray and Mr McDonald for the 1980 Royal Commission of Inquiry. This type of investigation is also the essence of this project. A study like this could be used to narrow down the time period when a questioned cartridge was produced. This could be followed by microscopic comparisons with cartridges from the relevant time period in order to define more specifically what bunter was used to produce the headstamp and the exact production date.

2 – MANUFACTURE OF .22 LONG RIFLE CARTRIDGES

The Colonial Ammunition Company (CAC) manufactured .22LR cartridges in New Zealand using cartridge cases produced by Imperial Chemical Industries (ICI) in Melbourne, Australia [3].

ICI was originally formed in the United Kingdom in 1926 from the amalgamation of four chemical companies. Following this, the Australian and New Zealand subsidiaries of these chemical companies became Imperial Chemical Industries of Australia and New Zealand (ICIANZ) [16]. The company name changed from ICI to Imperial Metal Industries in 1971 [2]. [In this thesis the company will be referred to as ICI].

CAC was an ammunitions manufacturer in New Zealand which was founded in 1885 [7]. CAC originally limited ammunition production to that of the large military calibres, but in February 1946 an agreement had been reached to produce and sell .22LR ammunition in conjunction with the Australian counterpart of ICI. The agreement was that .22LR cartridge cases would be manufactured and primed at the ICI factory at Deer Park, Melbourne, Australia (which will be referred to as ICI Australia). The empty cartridge cases were shipped to the CAC factory in Auckland. At the CAC factory, bullets were produced and loaded into the cases with the appropriate propellant. Production of .22LR ammunition at CAC began on 29th June 1948 and continued until the closure of CAC in 1983. The closure of CAC was the result of decreasing sales and the unwillingness to sustain trading losses [3].

2.1 .22 LONG RIFLE CARTRIDGES

Prior to detailing the manufacture of .22LR cartridges, it is important to introduce the various features of the cartridges. The main components of a cartridge include the cartridge case, primer, propellant and bullet (Figure 2.1).

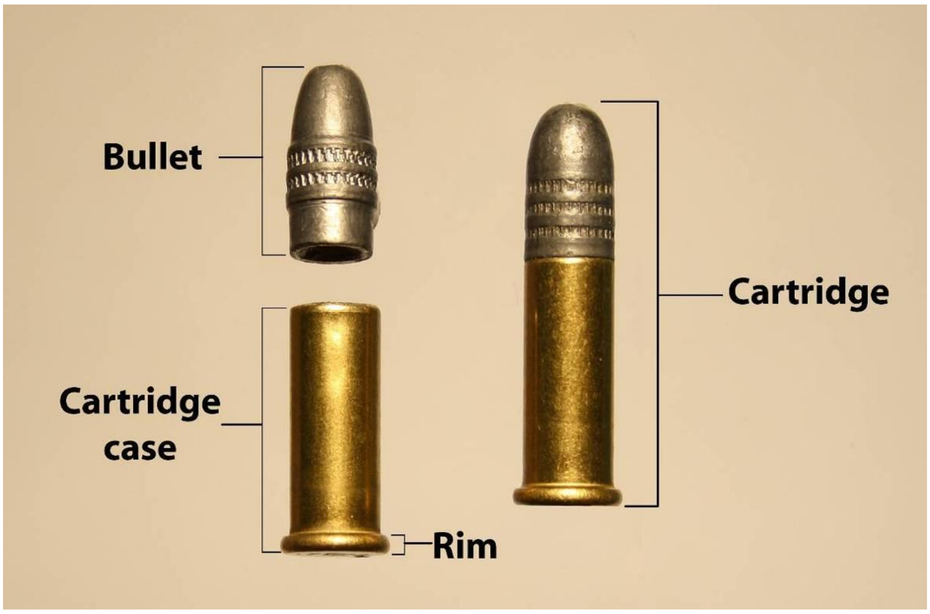


Figure 2.1: Photograph of a .22 Long Rifle cartridge (right) and a dissected cartridge (left) showing the various components.

The cartridge case is usually made of brass and it contains the primer, propellant and holds the bullet. At the base (head) of the cartridge case there is a prominent rim. The primer is an impact-sensitive explosive which resides within the rim and provides the initial combustion to facilitate the ignition of the propellant. The firing pin from the firearm must strike the rim of the cartridge case in order to crush the primer and start the combustion process. This feature is where the name “rimfire” is derived. The firing pin impressions left on the rim of some fired cartridges can be seen in Figure 2.2. Once ignited, the burning of the propellant produces a large amount of gas which propels the bullet down the barrel of the firearm. Various types and amounts of propellant are used in different cartridges to achieve different bullet velocities.

Figure 2.2: Photographs showing the firing pin impressions left on the rim of fired cartridge cases.

During manufacture the cartridge case has a headstamp impressed on the head of the cartridge (see 2.2.6). The headstamp is a manufacturer’s mark to show the brand or who manufactured the cartridge case. In some instances the headstamp may also state the calibre of the cartridge and the date of manufacture. Some .22 rimfire headstamps are shown in Figure 2.3.

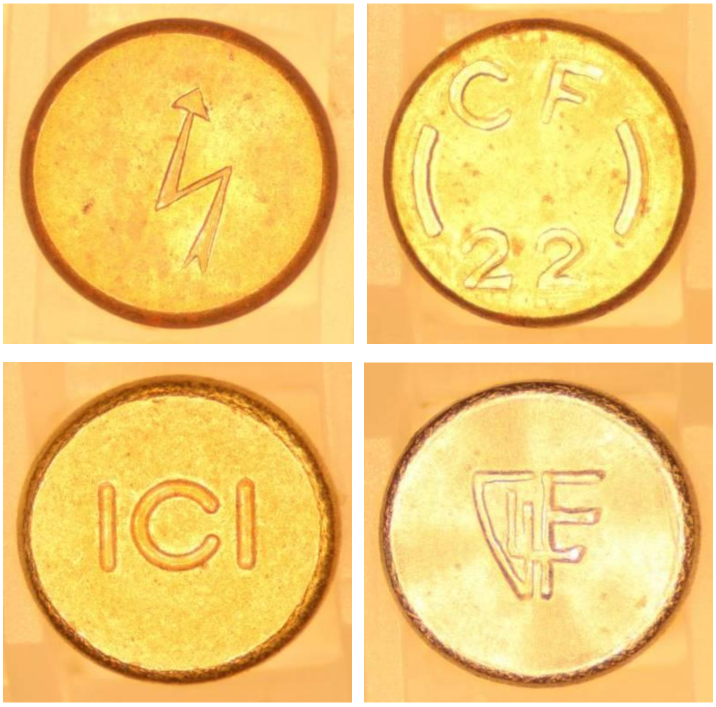


Figure 2.3: Four different headstamps on .22 Long Rifle cartridges.

The bullets (projectiles) are typically composed of an alloy of lead and antimony. The bullet is seated in the open end of the cartridge case and upon firing, the bullet is propelled down the barrel of the firearm. Bullets can have a solid or hollow-point (Figure 2.4). A hollow-point bullet has a cavity in its tip and is intended to cause the bullet to expand, or mushroom, upon entering a target.

Figure 2.4: Cross section of three cartridges. Left: .22 Long Rifle cartridge with hollow-point bullet. Centre: .22 Long with solid bullet. Right: .22 Short with hollow-point bullet.

The term “Long Rifle” refers to the calibre and relates to the length of the cartridge case and size of the bullet [2]. There are three main varieties of .22 rimfire cartridges, these are: “Short”; “Long” and “Long Rifle” (Figure 2.4). The .22 Short cartridges have the shortest cartridge case with the Long and Long Rifle cartridges having a longer cartridge case. The .22 Long has a smaller bullet than the .22LR cartridges. As Long and Long Rifle cartridges are longer, they can contain more propellant and therefore have a higher bullet velocity than .22 Short cartridges.

2.2 CARTRIDGE CASE MANUFACTURE

The specific manufacturing process of .22LR cartridge cases at ICI Australia is unknown as this factory is no longer in operation and the manufacturing records have been destroyed. However, the manufacture of .22LR cartridge cases is a relatively standardised procedure.

The following information regarding the various steps in the manufacture of .22LR cartridge cases has been compiled principally from a reference where imperial measurements have been used [18]. Although the data collection for this project deals with metric measurements, the measurements in this section will not be converted into metric units so that consistency is maintained with the diagrams taken from textbooks.

The manufacture of .22LR cartridge cases can be divided into eight individual steps: blank and cup; anneal, pickle and wash; draw; wash and dry; trim to length; head; relief anneal; final pickle and wash.

Cartridge case manufacture begins with the raw ingredient of brass. Brass can be defined as any alloy of copper and zinc, however “cartridge brass” is specifically an alloy of 70% copper and 30% zinc. This particular ratio of copper to zinc provides the optimum strength, hardness and ductility for cartridge cases. Cartridge brass was the main alloy used for manufacturing cartridge cases at ICI Australia [3]. The other types of cartridge cases produced by ICI Australia included “gilding metal” and “nickel-plated” cases. Gilding metal was used to make cartridge cases with a characteristic copper-coloured appearance and is an alloy of 95% copper and 5% zinc. The gilding metal cartridge cases, which will be referred to as “copper” cases, were characteristic of military orders although these also appear throughout production in other CAC-brand ammunition. Nickel-plated cartridge cases were manufactured to be used specifically in “CAC High Speed Hollow Point” brand ammunition [3]. Made of cartridge brass with a nickel coating applied, these cases have a nickel-coloured appearance. For the purposes of this project, these cartridge cases will be referred to as “nickel” cases.

The following description of cartridge case manufacture is taken mainly from the text of “Ammunition Making” by Frost [18].

2.2.1 Blank and Cup

The first stage in manufacture is the formation of a cup from a strip of brass. The specific thickness of the strip of brass will be dependent on the particular machines in operation, however the thickness usually ranges from 0.0185” to 0.0195”.

The mechanism for producing the cup involves feeding the strip of brass into a double-action press. In the press there are two rams, where one ram resides inside the other (Figure 2.5). The outer ram carries the blanking punch which is a hollow cylindrical punch with a diameter of around 0.5790”. The inner ram carries the cupping punch which is a solid cylindrical punch with a diameter of around 0.291”. The blanking punch descends and blanks a disk out of the brass, which then falls into the die. This is followed by the cupping punch which is centred on the brass disk and pushes it through the die to form a cup. The end result of this process is a small brass cup with a diameter of approximately 0.33” and a length of approximately 0.25”. Each cup produced will eventually be formed into a cartridge case. This process is carried out repetitively on the brass strip as it moves through the machine. The more punches that are carried out on the strip the higher the “strip efficiency” between the ratio of cups produced and total brass strip weight.

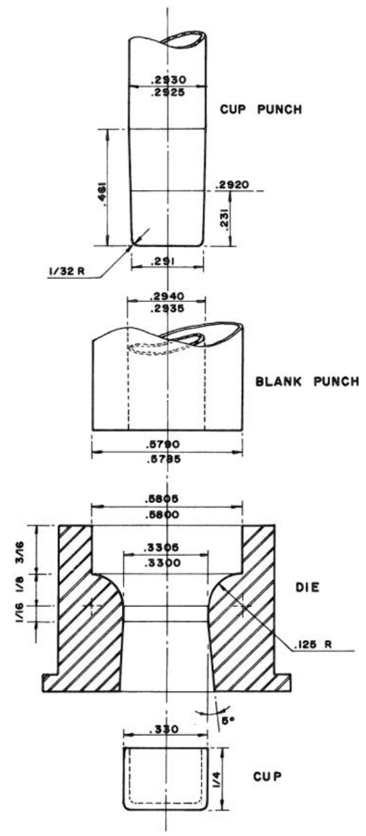


Figure 2.5: Schematic of the double-action ram showing the cupping punch, blanking punch and die which is used to form the brass cup [18].

2.2.2 Anneal, Pickle and Wash

Each cup is then sent to the annealing furnace where it is exposed to high temperatures (1150-1250 ^{o}F) for a short period of time (15-60 minutes). The annealing step is performed to soften the sides of the cup which become hardened from the cold working in the previous step. The bottom of the cup has not been worked to the same degree, so it is softer. Following annealing the cups are cooled in water, before being pickled in 4% sulphuric acid to remove the oxide scale formed during annealing. After pickling, the acid is rinsed and the cups are washed.

2.2.3 Drawing

The cups are then drawn out to elongate the cups and shape the cups suitably so that they are the correct length, thickness and diameter to be used as .22 ammunition. This is performed in a drawing machine and involves the cups being sat in a die where an internal punch repetitively pushes down on the cup to stretch and elongate the cup. Drawing can be performed by a single-draw process or a two-draw process. In the single-draw process the cup is drawn and elongated to its final diameter and wall thickness within a single drawing machine. In the two-draw process the cup is drawn to some extent in the first drawing machine before being annealed, pickled and washed. Following this, the cup is subjected to the second draw in a different machine which yields a cup with the appropriate dimensions for .22 ammunition.

2.2.4 Wash and Dry

Following drawing, the cups are washed, rinsed and dried.

2.2.5 Trimming

The cases produced from drawing are longer than what is needed so they must be trimmed to the appropriate size. Trimming is usually performed by a lathe-type machine. Usually, the case is picked up by a punch and pushed head-end first into a collet to the appropriate depth. The cutting tool then advances down and cuts off the open end of the case.

2.2.6 Heading

The next step in production is the formation of the rim and the impression of the headstamp. Up until this point in production the cartridge case consists of a blank-ended tube with an outside diameter of .22" and of a sufficient length to form the final cartridge. The formation of the rim and the impression of the headstamp are carried out in a single process. The heading tools and dimensions are shown in Figure 2.6. Additionally, if the cartridge case is to be primed by the dry-priming method this is also performed during this step (see 2.3.1).

The inside-heading punch (Figure 2.6) is loaded with a case, which is then fed into the heading die with the closed end of the case being fed in first. Once the case is fully fed into the heading die a small portion of the closed end of the case protrudes beyond the face of the die at the far end. The bunter (or header punch) has the reversed image of the headstamp embossed on it in raised print. As the bunter is forced against the bottom of the cartridge case, it causes considerable compression force on the metal. This force causes the expansion of the metal sideways, leading to the production of the rim of the cartridge case. As the hydraulic pressure increases, the raised design from the face of the bunter is also impressed onto the head of the cartridge case forming the headstamp.

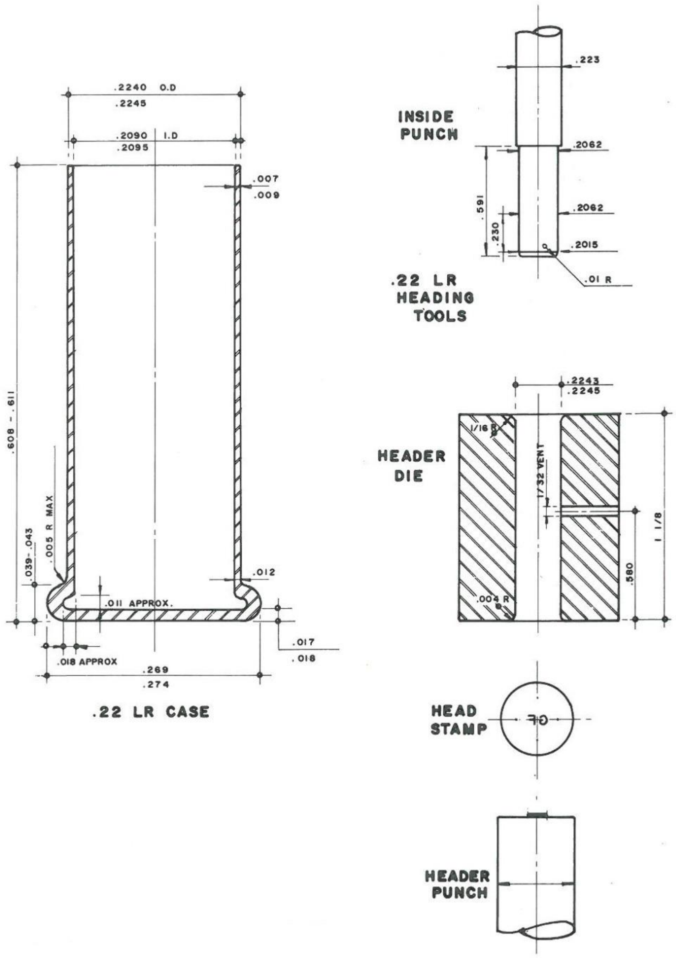


Figure 2.6: Schematic of heading tools and dimensions [18].

Further information regarding the formation of bunters and operating procedures at ICI Australia is documented in a subsequent section (see 2.4).

2.2.7 Relief Anneal

A relief anneal is necessary to ease the stresses in the head of the cartridge case caused by the sharp bending of the metal as the rim is formed. Failure to carry out this step could result in cracks forming across the rim of the cartridge case when fired, or spontaneous cracks could occur when stored for a period of time. The temperature of this anneal is usually held below 530^{o}F, however higher temperatures (575 ^{o}F) can be used if the brass is only exposed briefly.

2.2.8 Final Pickle and Wash

The final step to manufacturing cartridge cases is the final pickle and wash. The relief anneal leaves an oxide scale on the brass so the cases are pickled in 4% sulphuric acid to remove this scale. The pickled cases are then thoroughly washed, rinsed and dried.

If the cartridge cases are to be primed using the wet-priming method, this is performed immediately following this step (see 2.3.2). Otherwise each finished cartridge case is ready to be loaded with the appropriate propellant and bullet.

2.3 CARTRIDGE CASE PRIMING

There are two methods which can be used to prime .22LR cartridge cases. These methods are dry and wet priming. The different methods of priming acquire their names from the state of the primer during priming. The different priming methods are carried out at different stages of cartridge case production and the slight difference in the methods results in subtle manufacturing differences that can be seen on the exterior of the cases (see 2.3.4) [2].

2.3.1 Dry Priming

When cartridges are primed using the dry-priming method, the priming is completed during the “heading” stage of the cartridge case manufacture (see 2.2.6). Prior to a case being loaded onto the inside punch, a small (dry) solid disk of priming material covered with a small piece of foil is loaded into the case and forced to the bottom of the unformed cartridge case [2]. The inside punch then extends down the cartridge case until it touches the primer [4]. As the bunter is forced against the bottom of the tube, the hydraulic pressure increases considerably leading to the primer being pushed outwards and into the rim as the rim is being formed [2]. When dry-primed cartridge cases are viewed from the inside, the wall may be seen to be thicker towards the rim and the base will appear flattened with a squashed plug of priming mix (Figure 2.8) [3].

2.3.2 Wet Priming

Wet priming is performed after the final step of cartridge case manufacture. Wet priming uses a (wet) liquid slurry of priming material that is injected into the fully formed cartridge case [2]. Following primer injection, the cartridge case is spun at high speed, driving the mix into the rim by centrifugal force [4]. The rotation of the case continues while a blast of air is blown into the cartridge case to dry the slurry, leaving a solidified primer clinging to the inner surface of the cartridge case and inside the rim. When wet-primed cartridge cases are viewed from the inside, the interior wall appears straight and the priming mix can be seen as a circularly splayed ring of green deposit around the base (Figure 2.8) [3].

2.3.3 Priming at ICI Australia

It has been reported that most of the cartridge cases produced by ICI Australia up until around October 1974 were dry primed, however a small proportion were produced by the wet-priming method [19]. This was due to ICI Australia only having one machine capable of producing wet-primed cartridge cases [2]. Ian Cook, the Manager of ICI Australia, stated that up until 20th October 1965 the cartridge cases that were wet primed had been stamped with bunters of English manufacture [4]. The headstamps produced by these bunters are easily distinguished from the other headstamps of Australian manufacture as these have square-ended lettering (Figure 2.7) [2]. In order to keep the wet-primed and dry-primed cartridges distinct, the wet priming machine used the distinctive English bunters.

After 20th October 1965, the bunters of English manufacture became exhausted so the wet-priming machine was presumably re-tooled to take the bunters of Australian manufacture [2]. This suggests that the wet-primed cartridge cases produced after 20th October 1965 would have had the same headstamps as those seen on the dry-primed cartridge cases produced at that time.

Additionally, some wet-primed cartridge cases were obtained by CAC from sources outside ICI Australia. During the mid-1950's CAC obtained one million wet-primed cartridge cases from ICI England bearing what is known as the "Tenex" headstamp (Figure 2.7) [3]. The Tenex headstamp is similar to the headstamps of English manufacture which were produced by ICI Australia as both headstamps have characteristic square-ended lettering. However, the Tenex headstamp has noticeably thicker lettering. Cartridges bearing the Tenex headstamp were initially used as control cartridges by CAC in their accuracy cartridge development programme. By 1963, these cartridges had become superfluous to requirements so the remaining cartridge cases were loaded to make up military orders. This gave rise to unique boxes of ammunition containing wet-primed cartridge cases bearing the Tenex headstamp. These boxes are found periodically between batch numbers 3971 (packed July 1963) and 4055 (packed October 1963).

Figure 2.7: Photographs of headstamps with characteristic square-ended lettering. Left: A headstamp of English manufacture. Right: A Tenex headstamp.

2.3.4 Determining the Primed State of Cartridges

Determining the primed state of unfired cartridges is relatively straightforward. Unfired cartridges can be dissected, with the bullet and the propellant removed, so that observation of the base of the cartridge case is possible. Where a ring of green primer is seen splayed around the base, this indicates the cartridge case has been wet primed (Figure 2.8). Where this is not observed and instead there is evidence of a squashed plug of colourless primer with some remnants of foil, the cartridge case can be identified as being dry primed (Figure 2.8). Determining the primed state of fired cartridges by this method is not possible due to the removal of the priming material during firing. Similarly, this method is not able to be used on cartridges that have not been dissected.

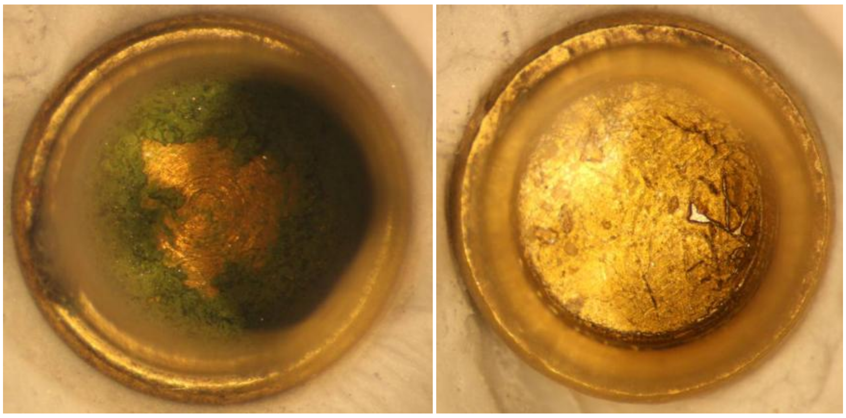


Figure 2.8: Photograph of the base of the cartridge cases as viewed from the inside. Left: Wet-primed cartridge case. Right: Dry-primed cartridge case.

During the trial of Mr Thomas, Dr Sprott postulated that he was able to determine how a cartridge was primed by analysing the rim of the cartridge under a microscope [2]. Dr Sprott described a subtle difference between dry-primed and wet-primed cartridges in that wet-primed cartridges had a broader and more rounded rim than that seen on dry-primed cartridges. The subtle difference in the rims of a wet-primed and a dry-primed cartridge can be seen in Figures 2.9 to 2.11. This difference arises from the subtle difference in rim formation between dry-primed and wet-primed cartridges. Determining the primed state of cartridges this way removes the need to dissect each cartridge. This method was used for determining the primed state of the cartridges sampled in this project, as it was not suitable to dissect each cartridge. Occasionally cartridges were dissected to confirm the exterior examination.

Figure 2.9: Photograph showing the physical differences in the rims between wet-primed and dry-primed cartridges. Left: A wet-primed cartridge case with the characteristic rounded rim. Right: A dry-primed cartridge case with the flattened edge of the rim adjacent to the case wall.

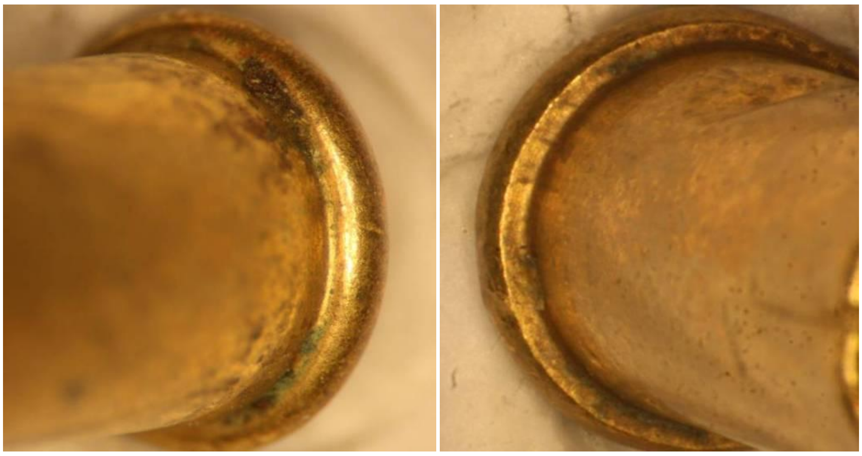


Figure 2.10: Photographs showing the subtle difference between a wet-primed (left) and dry-primed (right) cartridge.

Figure 2.11: Photographs of the head of a wet-primed (left) and dry-primed (right) cartridge. The wet-primed cartridge has a noticeably broader and more rounded rim at the base.

The method of priming had importance in relation to the trial of Mr Thomas for the Crewe murders. It was generally accepted that exhibit 350 (the cartridge case found in the Crewe garden) was dry primed [2]. This is what would be expected for a cartridge bearing the sans-serif-ICI headstamp, as this design of headstamp was used between 1960 and 1973 when the majority of cartridges produced by ICI Australia were primed using the dry-priming method [3]. However, determining the primed state of cartridges was more important during the 1980 Royal Commission of Inquiry where this aspect was used to dismiss a cartridge presented by Dr Donald Nelson (exhibit 1964/2) which was wet primed but asserted to have the same headstamp as exhibit 350 [2].

2.4 CAC HEADSTAMPS

CAC began producing .22LR ammunition in 1948 and production ceased at the closure of the CAC factory in 1983 [17]. In the 35 years of production, eight general designs of headstamp were observed, not including non-headstamped cartridges that were packed into some boxes towards the end of CAC's production [3]. The eight general designs of headstamps and the years in which they appeared are shown in Figure 2.12.

Figure 2.12: The eight general designs of headstamps seen on cartridges used by CAC [3].

Although there are eight general designs of headstamp, there were also a considerable number of variations within some of the designs [3]. The particular design of headstamp that was focused on in this project was the sans-serif-ICI headstamp (used between 1960 and 1973). Dr Sprott has already identified a number of class variants of the sans-serif-ICI headstamp [2]. The graphical demonstration showing the bivariate analysis of horn angle and overall letter width of the sans-serif-ICI headstamp outlined three different categories which Dr Sprott named "Category 3", “Category 4”, and “Wide I” (Figure 1.5). An example of each of these categories is shown in Figure 2.13. Further variants which were not identified in Dr Sprott’s analysis include the Tenex headstamps and the headstamps of English manufacture (Figure 2.7).

Figure 2.13: The different categories of sans-serif-ICI headstamps. Left: Dr Sprott’s Category 3. Middle: Dr Sprott’s Wide I. Right: Dr Sprott’s Category 4.

2.4.1 Bunter and Hob Production

The changes in headstamps that were observed in cartridges used by CAC were the direct result of manufacturing processes that occurred at ICI Australia. Headstamps are formed by a bunter during the heading stage in cartridge case manufacture (see 2.2.6). A bunter is a small steel tool that has the raised reversed design (or mirror image) of the desired headstamp on its surface, so that when the bunter is pressed against the cartridge case, the design is impressed into the cartridge case [2]. Bunters are produced from a hob. A hob is a steel tool which has the lettering of the desired headstamp engraved into its surface.

At ICI Australia, the hobs were engraved by C. G. Roeszler & Sons Pty. Ltd (in Melbourne) to the specifications provided by ICI Australia. The engraving of hobs was performed by a pantograph machine, which enabled large templates of letters to be reproduced on the hob at a given smaller size. The letters engraved on the hob were very small and the pantograph machine did not enable a sufficient size reduction, therefore an intermediate template was produced on a piece of scrap metal. The intermediate template was then used as the template for engraving the hob. Each time a new hob was made, a new intermediate template was produced (as this was easier than trying to locate past templates) [2].

ICI Australia manufactured their own bunters from the hobs provided by C. G. Roeszler & Sons [2]. A large number of bunters, up to around 450, were made at any one time from a particular hob. The process of forming a bunter involved the production of a soft blank in the toolroom at ICI Australia [20]. To form the raised lettering on the bunter, the soft tool blank was placed end to end against the engraved print on the hob and then forced against it in a hydraulic press. The hydraulic pressure was such that the softened bunter would flow into the incursed print of the hob, forming a reversed replica on the bunter. Following this, the bunter would be hardened and tempered. Prior to use, the bunters would be chromed so that during use, the chrome would wear off leaving a less damaged bunter. A bunter reportedly had an average life of around one day after which it would be assessed and re-chromed [19]. Bunters could be re-chromed around six to ten times before the lettering was too damaged to give a distinct print. At this point, the bunter would be discarded and replaced by another.

2.4.2 The Heading Operation at ICI Australia

At ICI Australia there were 24 heading machines capable of manufacturing .22 cartridge cases [2]. It is estimated that around ten of these machines were employed in the manufacture of .22LR cartridges at any one time, with the remainder of the machines being re-tooled or under maintenance. Each machine was capable of making approximately 100 headstamps per minute which equates to about 40,000 per day. Therefore, the overall production at ICI Australia was about 400,000 cartridges per day, of which only a small portion was shipped to New Zealand. ICI Australia also loaded cartridges for the Australian market.

With regard to the number of bunters made from a hob and the number of headstamps produced by each bunter, it is important to understand that a large number of identical, or very similar, headstamps were manufactured from any single hob [2, p32]. Furthermore, each type of headstamp, stemming from a single hob, would remain in production for an extended period until the bunters from the hob became depleted and the hob was too worn to produce more bunters.

2.4.3 Hobs, Bunters and Headstamps

Due to the relationship between hobs, bunters and headstamps, it’s important to understand that it was the replacement of hobs which resulted in the production of different headstamps. Although the bunters were not hardened until after being stamped by the hob, there was still considerable wear on the hob which eventually resulted in the need for replacement [3].

The hobs which were produced by C. G. Roeszler & Sons were made according to tool drawings which specified the appropriate measurements of the features of the headstamps (e.g. letter heights and letter spacing) with the appropriate tolerances [2]. The differences seen between the eight general designs of headstamps produced by ICI Australia (Figure 2.12) was the result of distinctly different tool drawings used by C. G. Roeszler & Sons to engrave the hobs.

However, there are perhaps four main reasons for the differences seen in the class variants within a particular headstamp general design;

1. In the same way that the general designs of headstamps differed, a different tool drawing could have been used by C. G. Roeszler & Sons that specified the same general design of headstamp, but with subtle differences in various aspects. For instance, a hob with the letters "ICI" engraved in sans-serif font, but with subtle differences in the height of the letters and the spacing of the letters.

2. Hobs bearing slightly different designs could have been produced from the same tool drawings. At the 1980 Royal Commission of Inquiry, George Leighton, Works Foreman of C.G. Roezler & Sons, explained how hobs were made and subsequently how differences would arise between hobs made from the same drawing. Mr Leighton stated that due to the "engravers choice" it would be unlikely that hobs engraved from the same drawings on different occasions would be identical [2]. The "engravers choice" can be outlined as follows:
    - The tool drawings that were given to C. G. Roeszler & Sons had tolerances for the measurements. These tolerances, although small, made it unlikely that the engraver would achieve the same result within the tolerances on each occasion.
    - The tool drawings allowed the engraver some license as to how the letters were positioned. The engraver would position the letters in a manner that looked pleasing to the eye, however this would likely change on occasion and from engraver to engraver. This can be shown in the various categories of sans-serif-ICI headstamp with the positioning of the letter "C" relative to the Letter "I" (Figure 2.13).
    - In the tool drawings there were no specifications regarding how far apart the "horns" of the letter "C" should be. Again the engraver would create a "C" that looked most pleasing to the eye, which is likely to change in different circumstances. This is evident when comparing Dr Sprott's Category 3 headstamp to the Category 4 headstamp, where the horns are much closer together in the Category 4 headstamps (Figure 2.13).

3. Another possible source of difference between hobs produced from the same drawing results from the state of wear on the cutting tool [2]. If the end of a cutting tool had

become worn, it would still be possible to cut the hob to the desired depth by lowering the tool slightly. This would result in the widening of the lettering.

4. Class variants of the sans-serif-ICI headstamp could have been produced by processes irrelevant to the manufacture of the hobs. Hobs became worn over time from repeated use. The wear on the hobs may have distorted the lettering of the hobs which would lead to the production of variant bunters. In the same way different bunters could have been produced from the same hob, different headstamps could have also been produced from the same bunter. Bunters were also subject to wear from repeated use which could have lead to distorted lettering and therefore variant headstamps.

2.4.4 Headstamp Overlap

There was an overlap between the headstamps used during different time periods. There are a number of reasons for this. Firstly, some headstamps were used periodically for a specific brand of ammunition. For instance, the small-CAC headstamp design was used between 1966 and 1973, the same general time period in which the sans-serif-ICI headstamp was used [3]. However, the small-CAC headstamp was intended to be used specifically for "High Speed Hollow Point" nickel-plated .22LR cases. During the seven years that the small-CAC headstamp was in use, it was limited to this brand of ammunition (there are some exceptions due to human error) whereas all other brands of ammunition at the time had the sans-serif-ICI headstamp.

Another reason that led to the cross over between headstamp designs revolves around the changeover of bunters from an old design to a new design. There were around 24 machines capable of producing headstamps at ICI Australia [3]. Upon bringing in a new style of headstamp, the old bunters were replaced by new style bunters as they became worn out. The old-style bunters would wear at different rates leading to some machines being changed to the new style bunter, whilst other machines continued to operate with the old-style bunters. This would lead to the production of some cartridge cases bearing the new-style headstamp and others bearing the old-style headstamp.

Additionally, further mixing of headstamps could have occurred during the processes after cartridge case manufacture (see 2.5).

2.5 PACKAGING AND SHIPPING TO CAC

Following cartridge case manufacture and priming, each cartridge case passed through a separator unit, to remove any loose primer on the case, and then into machine tote boxes [20]. Cases had a tendency to reside in the separator for long periods of time allowing differently headstamped cases to mix. After tote boxes were emptied, the cases were put in a large sawdust-filled rotating drum (known as a rumbling barrel), in lots of about 30,000 to remove any final loose primer. The same rumbling barrel was used for all cartridge cases, hence this allowed further potential mixing of headstamped cases. Upon removal from the rumbling case, the cartridge cases were inspected by the Inspection Department of ICI Australia before being boxed and sent to New Zealand. In some instances the Inspection Department would hold back cartridge cases (in the order of 250,000) for up to several months before being rejected or cleared for shipping to New Zealand allowing further mixing of the headstamps.

Each box of cartridge cases destined for New Zealand contained approximately 22,000 cartridge cases [21]. The number of boxes per shipment varied according to the demand of the CAC factory and records show this varied between 6 boxes and 196 boxes [5].

Upon arrival of the shipments to the CAC factory, it was normal practice to mark the shipment with the name of the vessel from which it came and the arrival date in New Zealand [21]. These records were essential so that if any defects were detected they could be traced back to a particular shipment [5, 21]. Once marked, the boxes of cartridge cases would be stored in the storeroom until they were issued to the loading section of CAC [20].

The shipments were generally used in the order in which they had come and each shipment would be used in its entirety prior to another shipment being started [21]. However, some exceptions to this have been observed where boxes were left half empty for some time before being finished at a later date [5, 21]. This allowed further mixing of the headstamps.

2.6 BULLET MANUFACTURE

Bullet manufacturing was performed at the CAC factory by specialised bullet forming machines that had been obtained from ICI Australia [3]. Bullet manufacture is a relatively simple process composed of two main stages, bullet forming and bullet canneluring [20].

2.6.1 Bullet Forming

Bullet formation starts with a length of wire composed of an alloy of lead and about 1-4% antimony [18]. Antimony is added to the lead as a hardening agent as pure lead is too soft to be used effectively as a projectile. A short length of the lead-alloy wire is cut off and directed into the bullet forming die [20]. A simplified schematic of the bullet forming die used at CAC is shown in Figure 2.14.

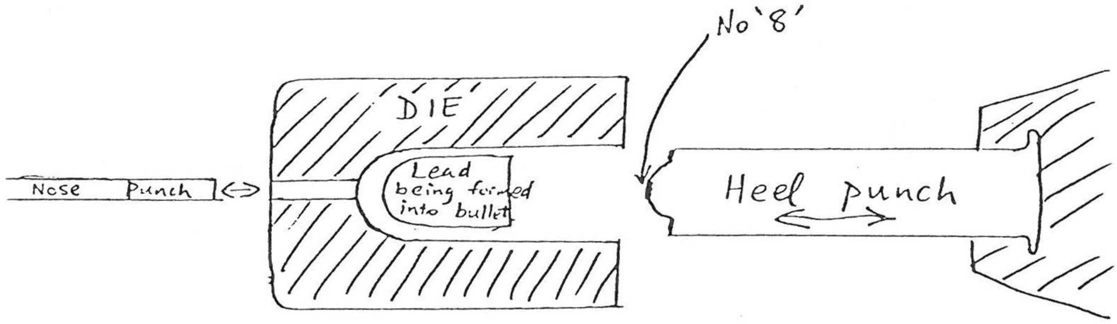


Figure 2.14: Simplified schematic of the bullet forming die used at CAC [20].

The heel punch forces the lead wire into the die where the lead is pressed into the general shape of a bullet. The shape of the die dictates the shape of the bullet ogive (the curved forward part of the bullet). The heel punch has a raised face, which leads to the production of a concaved base on the formed bullet [20]. The heel punch may have had a number or design impressed on its raised face in order to produce the reverse of the design on the base on the bullet for identification purposes (see 2.6.3.1). The nose punch assists in shaping the nose of the bullet depending on whether the bullet is hollow-point or solid [20]. For a hollow-point bullet, the nose punch would be pressed into the nose of the bullet to produce a hollow recess. For a solid bullet the nose punch would remain flush with the die to form a rounded nose on the bullet or conversely it is possible that a different machine lacking a nose punch would be used.

2.6.2 Bullet Canneluring

A cannelure is a narrow circumferential groove or knurling (series of indentations) formed around the body of the bullet [18]. The main function of a cannelure is to provide a groove to contain a lubricant to aid the passage of the bullet down the barrel of a firearm. Cannelures also serve as a means of identifying different bullet types as the types of cannelures may differ between bullet types in regard to style, number, spacing and width.

After the lead has been pressed into a bullet shape, the partially formed bullet passes through the canneluring machine [20]. Once in place, a cutting wheel with a sprocket-like shape is used to pass over the bullet and form the canneluring groove [18]. For bullets that have multiple cannelures, the cutting wheel has multiple cutting bands. The canneluring machine is also the site where the diameter of the lower part of the bullet is reduced to form a heel so the bullet can be seated in a .22LR cartridge case [20]. Some bullets also have other features, such as a lead-knife groove, applied to the bullet during canneluring. Finally, a waxy lubricant (usually paraffin) is applied to the bullet.

A labelled photograph of the various features of a bullet can be seen in Figure 2.15.

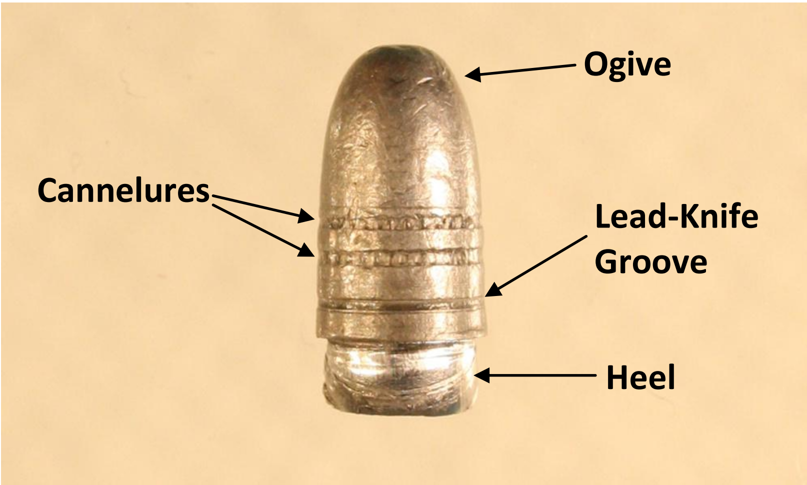


Figure 2.15: Labelled photograph of a bullet showing the ogive, heel, cannelures and a lead-knife groove.

2.6.3 Bullets Produced by CAC

At CAC the lead for bullet production was purchased from Battery Smelters Ltd. in Onehunga [3]. The lead was melted down in one tonne lots with added antimony and probably the addition of scrap from past bullet production. The composition of the sporting and field bullets (Pattern 8, 18 and 19) was approximately 97% lead and 3% antimony. The Pattern 20, or Mark10 accuracy bullet, contained 98.875% lead and 1.125% antimony and the Rifle Club and Palma bullets contained around 2-3% antimony with the remainder lead.

There were some alterations to the bullet-producing machinery during the period of manufacture resulting in the production of several different bullet types. A study of the production over the 35 years that CAC produced .22LR cartridges showed that six different designs of bullets were used [3].

2.6.3.1 *Pattern 8 Bullet*

The Pattern 8 bullets were the first design of bullet [3]. This bullet type was originally designed and used by ICI in England (ICI England). The bullet-producing machines at the CAC factory in New Zealand were obtained from ICI Australia, which in turn had been obtained from ICI England. This probably explains why this bullet design was originally used at CAC. Pattern 8 bullets are characterised by three cannelures and a very rounded ogive (Figure 2.16). Pattern 8 bullets were produced as either solid or hollow-point. All Pattern 8 bullets carry a raised “8” on the base (Figure 2.17), due to an impressed “8” being present on the face of the heel punch during bullet forming (see 2.6.1). Pattern 8 bullets were used in all “ ICI Long Rifle High Velocity” and “Standard Non-Rusting” cartridges between 1948 and 1963 with records showing that the last batch loaded into brass cartridge cases occurred on 10th October 1963 and the last batch loaded into copper cartridge cases occurred on 8th November 1963 [2, 3, 5].

Figure 2.16: Photograph showing the side view of a solid Pattern 8 bullet.

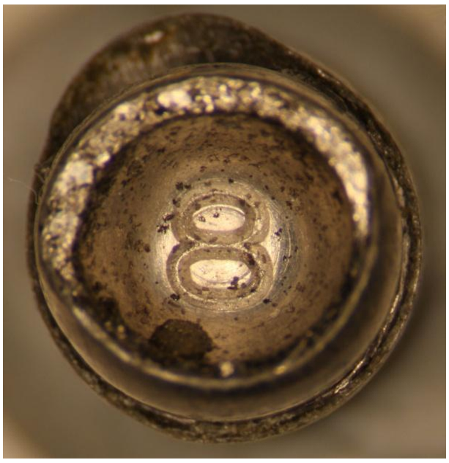


Figure 2.17: Photograph showing the embossed number 8 on the base of a Pattern 8 bullet.

There were also some cartridges which were imported from ICI England which appear to be loaded with Pattern 8 bullets. The similarities in design obviously arise from the similar origins of the machinery used at the ICI England factory and the CAC factory in New Zealand.

However, the Pattern 8 bullets of English origin contained a slightly differently shaped “8” or the letter “H”, or nothing on the base.

2.6.3.2 Pattern 18 and Pattern 19 Bullets

The Pattern 18 and Pattern 19 bullets were developed to replace the Pattern 8 solid and hollow-point bullets respectively [3]. The design of the Pattern 18 and 19 bullets were essentially identical with both having two cannelures and a less rounded and more pointed ogive than that seen on the Pattern 8 bullets (Figure 2.18) [2]. Neither Pattern 18 nor Pattern 19 bullets had numbers stamped on their base (Figure 2.19), although it has been speculated that it was possible some may have been stamped with an “8” (see 2.6.4). Pattern 18 and Pattern 19 bullets were used in all “ICI Long Rifle High Velocity” and “Standard Non-Rusting” cartridges from 13th November 1963 until CAC closed down in 1983 [3].

Figure 2.18: Photograph showing the side view of a Pattern 19 bullet.

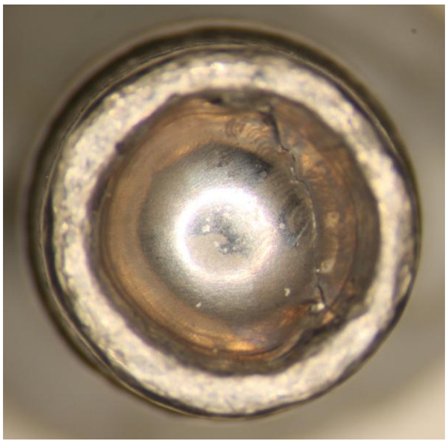


Figure 2.19: Photograph showing the base of a Pattern 19 bullet with no embossed numbers or lettering.

2.6.3.3 Palma Bullet

The Palma bullet was produced as an experimental bullet for accuracy testing. The Palma bullet was first recorded in CAC records on 29th August 1961 and finally on 24th February 1966 [3]. This type of bullet was found mainly loaded into cartridges in military boxes of ammunition, however it was also seen in a few commercially sold boxes. Palma bullets were usually loaded into copper cartridge cases, some of which had a single case cannelure approximately halfway down the case. There are also exceptions where they were loaded into brass cases. Palma bullets have a similar overall shape to Pattern 8 bullets, however they have only two cannelures which lie above a heavy lead-knife groove (Figure 2.20). Additionally, the ogive of Palma bullets has a slightly larger radius and the bullets are slightly more pointed than Pattern 8 bullets. Some, or all, Palma bullets carry a raised "8" on the base identical to that seen on Pattern 8 bullets. This is probably the result of using the same bullet forming machine as that of the Pattern 8 bullets.

Figure 2.20: Photograph showing the side view of a Palma bullet.

2.6.3.4 Pattern 20 Bullet

The Pattern 20 bullet was the end result of experimental bullet designs developed for the "Mark10" accuracy cartridge [3]. Pattern 20 bullets were similar to the Palma bullets in regard to having two cannerlures above a lead-knife groove, however the Pattern 20 bullets have a less rounded and more pointed ogive than that of the Palma bullets and the lead-knife groove was less pronounced (Figure 2.21). Pattern 20 bullets do not carry any markings on the base of the bullet. These bullets were loaded exclusively into "Mark10" brand ammunition, however some reject production was packed into "Standard Non-rusting" boxes.

Figure 2.21: Photograph showing the side view of a Pattern 20 bullet.

2.6.3.5 Pattern 8D Bullet

Pattern 8D bullets were similar to Palma bullets but these were unique to the military orders of ammunition in 1950 [3]. All Pattern 8D bullets carried a raised “8” on the base. Due to the time period in which these were used, they were not encountered during this project.

2.6.4 The Crewe Murder Bullets

When considering the type of bullets used in the murders of Mr and Mrs Crewe it’s important to consider the identifying features on the bullets in conjunction with the manufacturing techniques. Both of the bullets recovered from Mr and Mrs Crewe had sustained large amounts of damage and fragmentation [2]. The only significant feature that was able to be seen on the bullets was the number “8” embossed on the base of both bullets. The only bullet types produced by CAC that were known to carry the number “8” on the base were the Pattern 8, Palma and Pattern 8D bullets. However, in order to accurately determine more specifically which type of bullet was used in the murders, more information would need to be obtained about the other features of the fatal bullets (e.g. number of cannelures and bullet profile). The absence of these features on the recovered bullets was not unusual as these are often unable to be determined on bullets that have been captured in water where the bullet remains relatively intact [20].

That information aside, the presence of the “8” on the base of the recovered bullets was generally interpreted to indicate the bullets were of the Pattern 8 design, as this was the most widely distributed bullet available which had an “8” on the base.

It was proposed by Mr John Shea, former Superintendent of the .22 Ammunitions Section of ICI Australia and later the General Manager at CAC, that it was possible that some Pattern 18 and

Pattern 19 bullets may have been stamped with an “8” on their base [20]. His proposition revolved around the bullet manufacturing procedure at CAC. When CAC changed from making Pattern 8 to Pattern 18/19 bullets, it was necessary to re-tool the case canneluring machine in order to reduce the number of cannelures on the bullets from three to two. Additionally, the shape of the die used to form the bullets would have been slightly altered to accommodate the change in shape of the bullets. However, the heel punch dimensions for producing Pattern 8 and Pattern 18/19 bullets are the same so it would not have been necessary to replace the heel punch. The heel punch for Pattern 8 bullets carried the impressed figure “8” on its raised face which produced the embossed figure “8” on the base of the bullets. CAC would have had no obligation to change the heel punches during the changeover from Pattern 8 bullets to Pattern 18/19 bullets. The fact that Pattern 18/19 bullets might have been sold with the number “8” on their base was of no importance to CAC as the customer would never see the “8” on the base of the bullets.

It is possible that a similar process occurred when Palma bullets were produced. For instance, the bullet forming machine which originally produced Pattern 8 bullets would have had the canneluring machine re-tooled so that the appropriate Palma cannelures were produced. The bullet forming die may also have undergone slight alterations to change bullet shape. However, the heel punch did not need to be changed due to the similar dimensions. The resulting Palma bullet had a different profile and number of cannelures to the original Pattern 8 bullet, however the same heel punch was used which resulted in both types of bullets carrying a raised “8” on the base.

Despite the possibility of a Pattern 18 or Pattern 19 bullet having an “8” on its base, an example of such a bullet has never been reported. Some attempt to find such a bullet was performed by Dr Sprott, however the extent of the search was not documented.

2.7 CARTRIDGE ASSEMBLY

The final stage of manufacture is the cartridge assembly. Prior to loading at CAC, the cartridge cases received from ICI Australia were checked for size in a gauge plate to exclude overly small or large cases [20]. The cartridge cases were then sent through the loading machine where the cartridges were loaded with the appropriate propellant. Cartridges destined to be sold as a particular brand were loaded with the specific type and amount of propellant according to the brand requirements. From the loading machine the cartridges then entered the bullet press where the bullets were seated in the cartridge case to the appropriate depth. The final step involved crimping the cartridge case around the bullet to hold the bullet in the case and to form a seal [18]. This was performed by a specialised machine known as a crimper which closed the mouth of the cartridge case around the bullet. As an extra step to ensure the bullet-cartridge case junction was sealed, a crimp knife was used to push a small amount of lead from the bullet down over the junction. It was essential that the bullet was not held too tightly by the cartridge case as this could cause problems during firing. Conversely, it was important that the bullet was not too loose in the cartridge as this would allow moisture to enter which could also compromise firing.

2.8 BATCH NUMBERING

After assembly, the cartridges were packed into the appropriately branded boxes and the inside of one end flap of each box was stamped with the batch number. The presence of a batch number on each packet allows one to determine the date of manufacture from the CAC production records. The purpose of marking each box with a batch number is so CAC could identify the appropriate batch and production date if problems were later found with boxes of ammunition. During the early years at CAC, when there was a high demand for production, there were two batches of production on each working day with each batch producing approximately 60,000 cartridges [5]. This equates to a daily production of around 2400 boxes of ammunition. By about 1960 this had generally been reduced to a single batch of production of around 60,000 to 70,000 cartridges each day (around 1200 to 1400 boxes per day). However, as with most operations at CAC there are exceptions with periods of increased production presumably to accommodate increased demand [3, 5].

Finally the boxes were distributed to various ammunition dealers around New Zealand.

3 – DETERMINING THE OPTIMUM PHOTOGRAPHIC TECHNIQUE

Various techniques for recording images of the headstamps were considered for this project. These techniques were based on equipment that was readily available within the Physical Evidence laboratory of the Institute of Environmental Science and Research (ESR), or equipment that was obtainable at a reasonable price.

Factors that were considered when assessing each technique and ultimately used to decide which technique was used included: image quality; cost; availability; lighting options; time taken per image; consistency; and image reproducibility.

It was essential that the technique used for capturing images in this project provided high quality images. During image processing and subsequent data collection, the images were substantially magnified to maximise the accuracy of the data collected. There are many factors that contribute to image quality, however the main factor that was focused on was image sharpness. Sharpness describes the clarity of detail in an image [22]. The perceived sharpness of an image is determined mainly by image resolution and acutance.

Resolution refers to a camera’s ability to distinguish between closely spaced elements of detail. Put simply, resolution quantifies how close lines can be to each other and still be visually resolved. In terms of digital images, resolution is usually referred to as the number of pixels (picture elements) contained within the image. The higher the resolution of an image, the greater the number of pixels and therefore the larger the amount of information stored in the image. In digital imaging, the resolution is limited by the digital sensor of the image capture device (e.g. the charged-coupled device (CCD) of a digital camera) [23].

Acutance describes how quickly the image information transitions at an edge [22]. High acutance results in sharp transitions and detail with clearly defined borders. Acutance depends on the quality of the lens used and post-processing of the images. Acutance can be enhanced by digitally sharpening images using image editing programs such as Adobe Photoshop [23]. Due to the large number of images that were captured for this project, post-processing of images needed to be minimised. Therefore, it was essential that the image capturing device could provide sufficient acutance without the need for post-processing.

Lighting also plays a significant role in the production of high quality images [24]. In this project there was a need to show contrast between the headstamp and the head of the cartridge. Ambient light levels were not sufficient for photographing the headstamps so various light sources were trialled. Utilising a powerful light source allowed the use of shorter exposure times. Short exposure times were invaluable for techniques where there was potential of camera shake which can cause a substantial reduction in image quality due to blurring of the images. Additionally, a sturdy camera mount also helped minimised the effects of subtle vibrations of the camera during image capture.

The image capturing technique also needed to provide the appropriate magnification so that the head of the cartridge would fill the field of view. It was important to utilise the optical zoom as opposed to relying on digital zoom. Optical zoom refers to using a lens to magnify, or bring the subject closer to the capturing device [25]. This differs to digital zoom which involves cropping a portion of the image and then enlarging the cropped portion back to the original size. Utilising optical zoom allowed the production of maximum quality images.

Image focusing plays a large role in providing sharpness in images. Out-of-focus images have substantially reduced acutance. It was important for the image capturing technique to be easily focused so that high quality images were produced. Focusing of images was also important with regard to the time taken to capture the images. It was important that focusing of the images was not tedious and could be performed quickly so that images could be captured in a timely manner. For this reason it was also important that the image capturing technique could be set up quickly for capturing images. This project involved capturing hundreds of images. Therefore it was important that the chosen technique was able to quickly set up from day to day.

Cost was also considered in the decision-making process. Due to the large amount of images that were captured in this project, it was essential that the cost incurred per image was low. Techniques that utilise expensive equipment were not considered.

The technique used to capture the images should be consistent and produce reproducible images. The image-capturing process spanned many weeks and being able to capture the images consistently from day to day was important. Image consistency was essential for providing accurate data from the images captured on different days. The main factors addressed when considering image consistency and reproducibility were lighting (i.e. angle and distance from object) and magnification.

Capturing images on film can be ruled out for this project, despite it being accepted that the highest quality images are captured on film [23]. The cost associated with developing the films and producing enlarged prints of the images would have been too high. Additionally, the enlarged prints of the images would have to be manually processed, which would be time consuming. Furthermore, the quality of the images produced on film cannot be determined until the film has been developed. This means there is no immediate feedback on image quality compared to that which can be achieved with digital photography. This makes the method somewhat inconvenient and may have created problems with image consistency. For this reason, only digital photography or digital image capturing devices were considered for this project.

3.1 IMAGING TECHNIQUES

A single cartridge was used to trial each of the techniques described below. Images of the headstamp on this cartridge were captured using the various techniques, followed by subjective and objective analysis of the images produced. The results are summarised in Table 3.1.

3.1.1 Flat-Bed Scanner

Figure 3.1: Scan set up with three cartridges located in the centre of the scan surface.

A flat-bed scanner is a device which optically scans an image or object and converts it to a digital image [23]. Scanners utilise an internal light source and images are captured by an internal CCD array. Focusing of the images is done automatically by an internal lens. The scanner which was trialled for this project was a Hewlett Packard Scanjet 5400c. The scans were performed in True Colour (16.7 million colours) at the maximum resolution of 2400 pixels per inch. The cartridges were placed on the glass pane of the scanner with the headstamp facing downwards. The general set up is shown in Figure 3.1.

Scanning is a very simple technique as the lighting, focusing and image capture are all carried out internally. This provides excellent consistency and reproducibility between images, however the inability to have manual control over these processes also provides some problems for image quality. From observation of the images captured (Figure 3.2) there appears to be a slight focusing issue leading to a reduction in image sharpness. Additionally, the lighting intensity was unable to be increased or decreased and the angle at which the light was shone on the head of the cartridges was unable to be changed to enhance the contrast within the head of the cartridges.

Figure 3.2: A cropped image of a headstamp captured using the Hewlett Packard Scanjet 5400c.

An image distortion problem was observed in some images captured by the scanner. The problem appeared to arise from the angle at which the images were captured from. This was particularly evident when cartridges were placed at the left or right extremities of the glass pane of the scanner (Figure 3.3). In order to minimise the distortion effect, it was vital that the cartridges were placed in the centre of the glass pane of the scanner.

The images produced by the scanner have a pixel density of 2400 pixels per inch. This appears to be very high however the scanner does not utilise optical zoom so the images are captured in real size. The diameter of a head of a cartridge is approximately 7mm resulting in an image with relatively fewer pixels than one would expect (see Table 3.1).

Figure 3.3: Scanned image of a cartridge demonstrating the distortion effect. The cartridge was placed at the right extremity of the scanner's surface. The image was captured from an angle that allowed the case wall to be seen.

High resolution scanning of the cartridges was very time consuming. It took approximately 70 seconds to scan an area selected around a single cartridge. A solution to this problem involved scanning multiple cartridges at once. Approximately 40 cartridges were able to be scanned at once which took about 18 minutes. This reduced the time taken per image to around 27 seconds. However, the resulting file from such a scan was very large at around 63.4MB (Megabytes). The specifications for the computer available did not allow large images to be readily manipulated, resulting in slow processing.

This technique was not used for this project.

3.1.2 Digital Photography

The digital photography techniques utilised a Nikon D70s digital camera. The Nikon D70s has a pixel rating of 6.3 megapixels [26]. The images produced by this camera were 24.47cm x 16.93cm with a pixel density of 300 pixels per inch (118 pixels per cm). The camera was mounted on a copy stand to keep the camera fixed and to reduce camera shake.

In instances where a ring light was used, the ring light was a Leica CLS 150X ring light which was held in place by a clamp and stand. The flexible fibre-optic lights used were Kyowa FLG Flexible fibre-optic lights. The flexible fibre-optic lights had the advantage of being able to be easily moved so that the angle at which the light was directed at the head of the cartridge could be changed in order to show contrast in the head. However, this set-up decreased consistency and reproducibility between photographs. This problem was further complicated by the lack of stiffness in the arms of the lights and the tendency of the lights to sag over time. It was decided early on in the trials that the flexible fibre-optic lights were not suitable for this project and subsequently these were rarely used in the trials.

The use of the ring light, held in place by a clamp and stand, was much more suitable for trialling the various techniques. The intensity of the ring light was generally held at its maximum but could be adjusted if necessary. There were some inconsistencies with the lighting when the ring light was used for different digital photography techniques, mainly due to changes in the distance between the ring light and the cartridge. This distance was subject to change between the various techniques as it was governed by the relative working distance available. Additionally, the position of the ring light could have been changed when a particular technique was set up on different occasions. It was generally accepted that there were some inconsistencies when using the clamp and stand to hold the ring light, however these were relatively small.

The lenses available for the Nikon D70c were (bracketed measurements refer to the lens diameter):

- Nikon Lens Series E 50mm 1:1.8 (52mm).
- Nikon AF-S NIKKOR 18-70mm 1:3.5-4.5G ED (67mm).
- Nikon AF NIKKOR 70-300mm 1:4-5.6 G (62mm).
- NIKKOR 28-70mm 1:3.4-4.5D (52mm).
- Tokina 28mm 1:2.9 (52mm).

The various lenses available for the Nikon D70s were unable to provide sufficient magnification alone. Therefore, various methods for providing high quality close-ups of the headstamps were trialled. For each method the set-up which produced the highest-quality images were discussed.

3.1.2.1 Bellows and Extension Tubes

Bellows and extension tubes are devices which can be positioned between the lens and camera in order to increase the focal length which creates increased magnification [24]. The difference between bellows and extension tubes is that the extension tubes are of a fixed length whereas the bellows have an adjustable length. Bellows can be adjusted so that an optimum magnification can be achieved whereas extension tubes have set thicknesses of the tubes. For larger extensions, bellows are usually preferred over extension tubes due to fear of bending the tubes and damaging the camera from the overhanging weight of the tubes and lens. The bellows used in this trial was a Nikon PB-6 Bellows (Figures 3.4 and 3.5). The Nikkon PB-6 bellows permit an extension of the focal length behind the lens of up to 208mm for reproduction ratios of nearly 11:1 [27]. A reproduction ratio of 11:1 means the image is eleven times the size of the subject and therefore has been magnified eleven times.

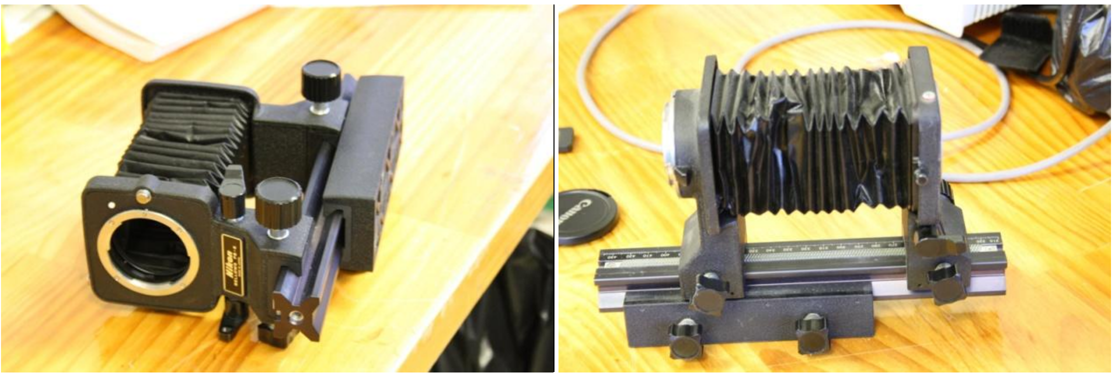


Figure 3.4: Photographs of the Nikon PB-6 Bellows.

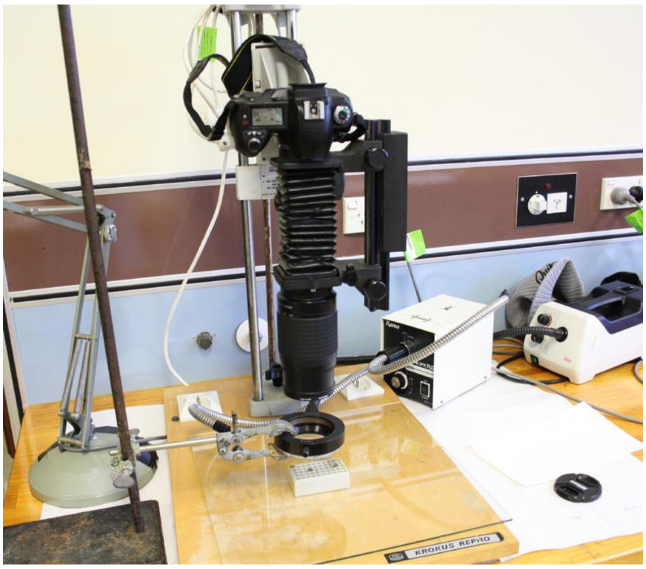


Figure 3.5: The set up for the photographs taken utilising the bellows. Note the use of the ring light which is held by the clamp and stand.

The extension tubes used in this trial were a set of three tubes: an 8mm PK-11a tube; a 14mm PK-12 tube; and a 27.5mm PK-13 tube (Figure 3.6). The three tubes can be used together to lengthen the focal length behind the lens by a maximum of 49.5mm. Conversely the tubes can be used individually or in pairs (Figure 3.7).

Figure 3.6: Photographs of the Nikon series of extension tubes. Left: Nikon series of extension tubes, 27.5mm PK-13 tube, 14mm PK-12 tube, 8mm PK-11a tube. Right: All three extension tubes mounted together

Figure 3.7: Photographs showing the camera with extension tubes attached. Left: 50mm lens mounted with the 27.5mm PK-13 extension tube. Right: 50mm lens mounted with all three (PK-13, PK-12 and PK-11a) extension tubes.

Various combinations of the extension tubes were used in conjunction with each of the available lenses, but in all instances the extension tubes were unable to provide sufficient lengthening of the focal length to obtain sufficient magnification. An example of the resulting images from the use of the extension tubes is shown in Figure 3.8.

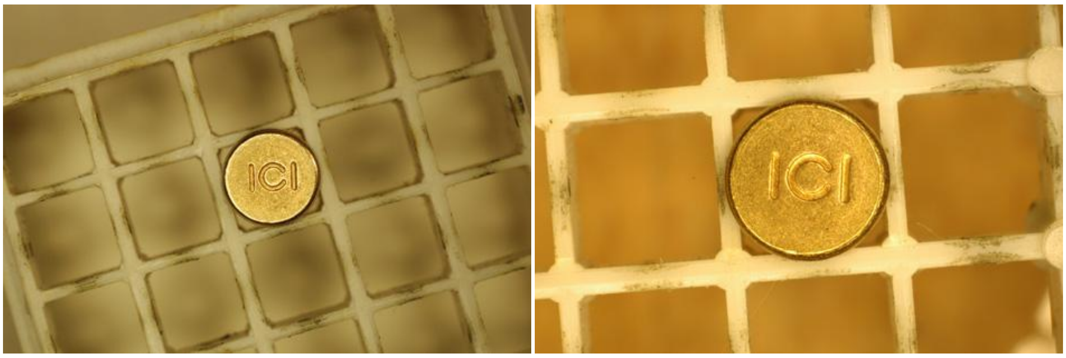


Figure 3.8: Photographs of a headstamp using the extension tubes (50mm lens). Left: Using the 27.5mm PK-13 extension tube. Right: Using all three extension tubes together.

Similarly, all lenses were trialled with the bellows. Although the bellows extends the focal length behind the lens, this results in a substantially reduced working distance. When the bellows was used with the 28-70mm and 18-70mm lenses, the working distance became too small, resulting in unsatisfactory images.

The best images from all the bellows-lens combinations were produced by the 70-300mm lens with the bellows extended to approximately 170mm. With this set-up the lens was set to around a quarter of its maximum zoom, resulting in a working distance of approximately 90mm, which allowed enough room for the ring light to be used as the lighting source. A photograph taken using this method is shown in Figure 3.9. Additional photographs were also taken using the flexible fibre-optic lights, however the ring light was the preferred lighting method. This method provided sufficient magnification of the headstamps and allowed the ring light to be positioned at a distance that allowed contrast to be shown between the head and the headstamp. Figure 3.9 was subsequently used for the resolution calculation contained in Table 3.1.

Figure 3.9: Photograph taken using the 70-300mm lens in conjunction with the bellows and the ring light.

There were several problems associated with using bellows and extension rings. The extended focal length leads to an increased distance for light to travel and reduced light reaching the sensor of the camera. This results in the need for longer exposure times. When using longer exposure times, the effects of subtle vibrations of the camera can lead to blurring of images and decreased image quality. This problem was further exaggerated when using the bellows due to the increased weight on the camera when mounted on the copy stand. The reduced stiffness in the copy stand complicated image focusing as the distance between the lens and the cartridge was subject to movement.

Focusing images when using the bellows was time consuming. The bellows must be lengthened to the desired length, the zoom and focus set appropriately and the working distance adjusted so that the image was in focus. Additionally, the aperture size must be selected and the correct exposure time used. Controlling these factors provides some difficulties for image reproducibility and makes this method tedious.

Neither the bellows nor the extension tubes were selected to be used in this project.

3.1.2.2 Close-Up Filters

Close-up filters are small lens attachments that can be screwed into the filter thread at the front of the lens (Figure 3.10). Close-up filters effectively provide a magnifying element in front of the camera lens to increase the size of the image projection [24]. Magnification is produced by shortening the focal length of the lens and allowing the photograph to be taken at working distances considerably closer to the subject. Close-up filters are inexpensive and very easy to use. The close-up filter available for use within the Physical Evidence laboratory was a JESSOP 52mm +3 lens attachment. This particular close-up filter can be mounted in front of any 52mm lens. The "+3" marking on the close-up filter refers to the dioptre, or power, of the filter. A dioptre value of +3 refers to the ability of the close-up filter to provide approximately 1.75 x magnification. The 28-70mm lens was able to provide the best close-up photographs in the absence of any external magnification techniques, therefore this lens was the most appropriate to be used with the close-up filter. The photographs were taken with this lens at maximum zoom and the lighting was provided by a ring light (Figure 3.11).

Figure 3.10: Photograph showing the 28-70mm lens and the JESSOP 52mm +3 close-up filter. Left: Lens and close-up filter (unattached). Right: Lens with close-up filter attached.

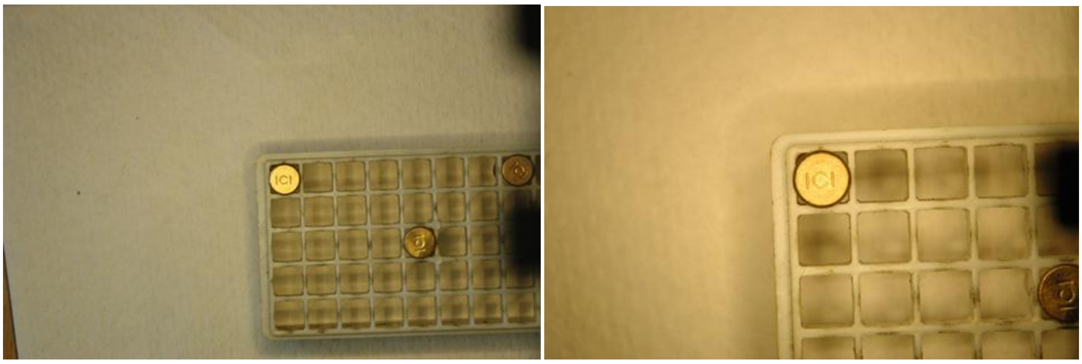


Figure 3.11: Photographs of a headstamp using the 28-70mm lens with and without a close-up filter. Left: Using the 28-70mm lens at maximum zoom in the absence of the close-up filter. Right: Using the 28-70mm lens at maximum zoom with the JESSOP +3 close-up filter.

As expected the close-up filter did provide some magnification of the head of the cartridge, however the magnification was still insufficient for what was required for this project. In order to further increase the magnification, it is possible to stack close-up filters on top of each other. This was not trialled because other filters were not available. There are also problems associated with stacking filters. Close-up filters are effectively a small piece of curved glass that attaches in front of the lens. Each close-up filter that is attached to a lens decreases the amount of light reaching the camera and increases image aberrations. Additionally, the depth of field of the image becomes reduced and longer exposure times are needed to allow sufficient light to reach the detector. Figure 3.11 (right) was used in the resolution calculation in Table 3.1.

The images produced by the close-up filter were deemed inadequate for this project and therefore this technique was not used.

3.1.2.3 Macro Lens

Macro lenses are specialised lenses capable of providing close-up images without the use of external magnifying techniques. Generally speaking, a macro lens provides a magnification ratio of around 1:1. This means that the image projected from a macro lens to the digital sensor (of a digital camera) is roughly the same size as the subject [24]. A Nikon AF Micro Nikkor 60mm F/2.8D macro lens was briefly trialled at the Auckland Camera Centre (646 New North Road, Morningside, Auckland). This was unable to provide sufficient magnification for what was required for this project. Due to the cost of macro lenses (in excess of $1000), this lens was not purchased and further trials were not conducted.

Had this lens been available, it may have been useful to have been used in conjunction with other equipment such as the bellows or the close-up filter. (An example of this is given by McDonald [24, p10-2] where a macro lens has been used in conjunction with bellows to produce good quality close-up images of .22 cartridges)

3.1.2.4 *Lens Coupling*

Lens coupling is an unconventional technique which can produce high quality close-up images [28]. Lens coupling employs the use of a lens-coupling adapter in order to join two lenses together. Lens-coupling adapters have two “male type” threads which are able to screw into the filter threads of two lenses in order to couple the lenses together. One of the lenses is attached to the camera in a normal fashion with the other lens reverse-mounted onto the first lens via the coupling adapter. The lens coupling set up is shown in Figure 3.12.

Lens coupling works by using the reversed lens to provide magnification of the subject, whilst the lens attached to the camera in the normal orientation is used to focus the resulting image onto the camera sensor.

Figure 3.12: Lens coupling. Left: Camera with (62mm) 70-300mm attached, next to a coupling adapter and a (52mm) 28-70mm lens. Right: Camera with (62mm) 70-300mm lens and the reverse mounted (52mm) 28-70mm lens coupled via the 52mm-62mm coupling adapter.

The coupling adapter which was available for the trials was a 52mm-62mm coupling adapter. As the name suggests, this adapter was capable of coupling a 52mm diameter lens to a 62mm diameter lens. From the lenses available, there were four different lens combinations which were trialled:

1. The (62mm) 70-300mm lens attached to the camera with the (52mm) 28-70mm lens in reverse configuration.

2. The (62mm) 70-300mm lens attached to the camera with the (52mm) 28mm lens in reverse configuration.
3. The (52mm) 28-70mm lens attached to the camera, with the (62mm) 70-300mm lens in reverse configuration.
4. The (52mm) 28mm lens attached to the camera, with the (62mm) 70-300mm lens in reverse configuration.

The four different configurations will be referred to as 1 – 4.

When using lens coupling it is important that the reversed lens has the aperture set to its maximum diameter to allow maximum light to reach the sensor. When using the 28-70mm lens and the 28mm lenses in reverse (Configurations 1 and 2), the aperture was manually adjusted to its maximum diameter using a mechanism on the lenses. However, when the 70-300mm lens was used in reverse (Configurations 3 and 4), a folded piece of cardboard was used to hold the aperture switch open (Figure 3.13) as this lens lacked a manual aperture adjuster.

Figure 3.13: Photographs showing how the aperture was held open on the reversed lens during lens coupling. Left: Photograph 70-300mm lens showing the aperture in normal closed position. Right: Photograph of the 70-300mm lens showing the aperture switch being held open.

All photographs produced from the various configurations of lens-coupling suffered from substantial vignetting. Vignetting refers to the unintended darkening which can be seen around the periphery of an image (Figure 3.14). There are a range of different mechanisms that can cause vignetting, however this type of vignetting is known as mechanical vignetting [29]. This occurs when the corners of the image sensor receive less light than it would in the absence of an extra lens. Essentially, the additional lens blocks the light from reaching the corners of the image sensor. The extent of vignetting that occurred with each of the lens configurations was dependant on the dimensions of the lenses used. When vignetting occurs there is a loss of field of view, resulting in a decreased maximum magnification that can be used to capture the images.

Another common feature to the images produced by lens coupling was a lack of sharpness in the images. This is common to lens-coupling techniques as the pictures become softer as a result of the extra glass (lens) for light to travel through in order to reach the image sensor.

Focusing was difficult when using this technique due to the narrow depth of field associated with lens coupling. In photography a common method to increase the depth of field involves reducing the aperture size, however this was not able to be done as this caused increased vignetting. Focusing images was further complicated by the increased weight of the camera (from the second lens) which caused decreased stiffness in the copy stand. The weight of the camera also contributed to increased camera shake. This combined with the need for longer exposure times produced subtle blurring and loss of image quality.

Configurations 3 and 4 were unable to provide sufficient magnification of the headstamps, whereas configuration 2 provided too much magnification to the extent that the whole head of the cartridge was unable to fit in the field of view. Configuration 1 produced the best quality images of those trialled and subsequently this image (Figure 3.14) was used in the resolution calculation contained in Table 3.1.

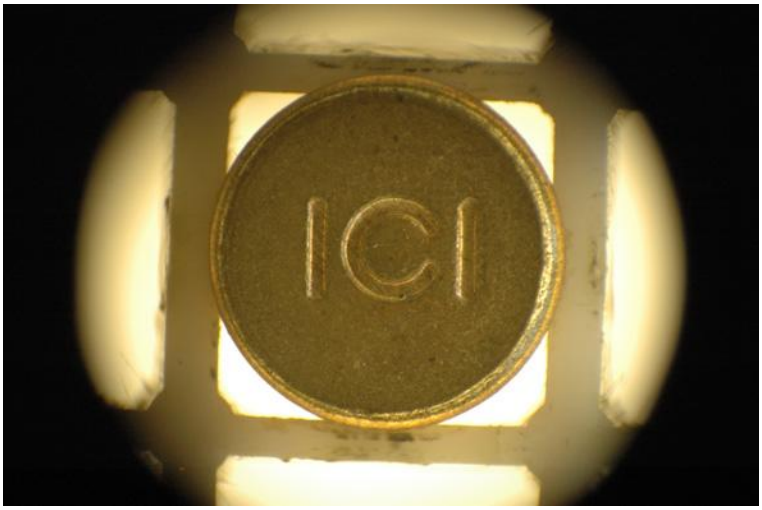


Figure 3.14: Photograph captured using lens-coupling Configuration 1.

Although this method could produce good magnification, it was unwieldy, did not produce quality images and was potentially inconsistent. The cost of a coupling adapter was relatively cheap ($25), however overall this technique was unsatisfactory.

The lens coupling technique was not used for this project.

3.1.2.5 Lens Reversing

The reverse mounting of lenses is another unconventional technique which can be used to achieve high magnification for close-up photographs [24]. A lens-reversing ring is used to provide the link between the reversed lens and the camera. The reversing ring has a “male type” thread, which screws into the filter thread of the lens, and a “male F-bayonet” which allows the reversing ring to be attached to the Nikon D70s camera via the Nikon-F mount. This allows a lens to be mounted on the camera body in the reverse configuration (Figure 3.15).

The lens-reversing ring available was able to be used with a 67mm lens. The only 67mm Nikon lens available was the 18-70mm lens. When using a reverse-mounted lens the automatic control over aperture size is lost therefore the aperture recedes to its smallest state [24]. It is important to keep the aperture open to allow sufficient light to reach the image sensor. The 18-70mm lens did not have a manual aperture adjuster so a piece of cardboard was used to keep the aperture switch fully open (Figure 3.13). This setting led to a narrow depth of field. This technique would be best used with a non-AF (auto focus) lens to allow adjustments of the aperture.

The 18-70mm lens was zoomed to approximately half its maximum zoom in order to provide sufficient magnification. The working distance was approximately 70mm and therefore a ring light could be used to provide the lighting. A photograph produced using this set-up is shown in Figure 3.16.

Figure 3.15: Photographs outlining the lens reversing set up. Top Left: Camera with 18-70mm lens mounted in a normal fashion. Top right: Camera with lens detached. Bottom left: Camera next to lens reversing ring and the reversed lens (all detached). Bottom right: Camera with lens in the reverse configuration via the lens reversing ring.

Figure 3.16: Photograph captured using reversed-lens photography. The reversed lens was the 18-70mm lens.

The photographs produced by the reversed 18-70mm lens were of high quality. The magnification was able to be optimized so that the field of view was filled by the cartridge. The images were sharp and there was good detail seen on the head of the cartridge. The photograph in Figure 3.16 was subsequently used for the resolution calculation in Table 3.1.

Using the reversed lens to capture photographs of the cartridges was a relatively simple technique. When using this technique, the focusing and zoom mechanisms were used in much the same way as when using a lens that is attached normally, however the actions were reversed.

The relative simplicity of this technique allows images to be captured in a timely manner with little inconvenience.

The cost involved with this technique was minimal as a lens-reversing ring was purchased for $20.

This technique was not used for capturing images of the headstamps in this project.

3.1.2.6 Photography Through a Microscope

Capturing images through a microscope was trialled using a Leica MZ6 bench microscope with a trinocular intermediate tube and SLR camera accessories which allowed the Canon 1000D digital camera to be mounted on the microscope. The Canon 1000D has a pixel rating of 10.1 megapixels [30]. The images produced by this camera were 137.16cm x 91.44cm with a pixel density of 72 pixels per inch (28.35 pixels per cm). The microscope uses a Leica CLS 150X ring light. The cartridges were first placed on the microscope stage and magnified using the adjustable zoom of the microscope. The images were subsequently brought into focus by adjusting the focusing mechanism on the microscope. The set-up for taking photographs through the microscope is shown in Figure 3.17. A photograph produced using this technique is shown in Figure 3.18. This photograph was subsequently used for the resolution calculation contained in Table 3.1.

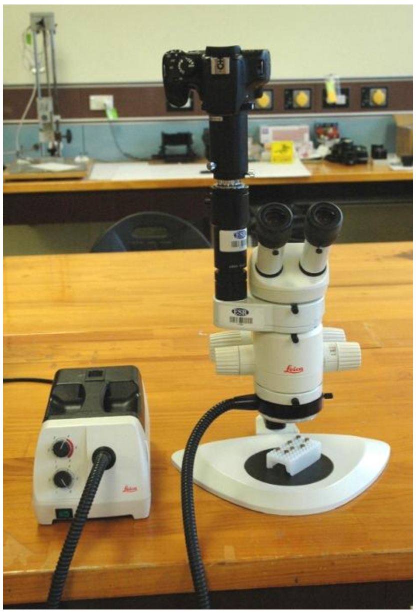


Figure 3.17: The set-up for taking photographs through the Leica MZ6 bench microscope with the Canon 1000D digital camera.

Figure 3.18: Photograph captured using the Canon 1000D digital camera through the Leica MZ6 bench microscope.

The photographs produced using this method were of very high quality. The photographs were of the highest resolution of all the techniques trialled (see Table 3.1). The adjustable zoom of the microscope allowed optimal magnification to be achieved easily. Focusing of the images was very easily performed using the focusing mechanism of the microscope. Obtaining optimal focusing was further assisted using the LCD display of the Canon 1000D for live view. When using the live view feature it was possible to zoom in on specific features of the cartridges with up to 10x digital magnification. Therefore, a small portion of the head of the cartridges was able to be zoomed in on and focused optimally to produce very high quality images. The photographs taken through the microscope appear to be the sharpest of all the photographs produced by the trialled techniques.

The ring light which was used to provide the lighting for these photographs was mounted on the microscope. As the ring light was physically fixed to the microscope, this removed problems with consistency and reproducibility that had been encountered for the other techniques. The distance between the ring light and the head of the cartridge remained consistent between images. Having the ring light mounted on the microscope provided the ideal lighting conditions for capturing the photographs.

The microscope used did not allow the aperture size to be adjusted, therefore all photographs were captured using an aperture of a set size. Although the specific size of the aperture is not known, there were no problems encountered regarding the depth of field.

Taking photographs through the microscope was very straight forward. Optimal magnification and focusing were attained very quickly, allowing images to be captured in a timely manner.

The microscope used was sturdy and was subject to minimal movement during the capture of images. This reduced problems associated with blurring of images from camera shake. Additionally, the lighting provided was of a high intensity that allowed very short exposure time, further negating the effects of subtle vibrations of the camera during photographing.

There were no additional costs incurred for this technique as this set-up is routinely used within the Physical Evidence laboratory for photographing exhibits.

This method produced the greatest quality images and was the most superior technique trialled for this project. Therefore, this method was selected to be used in this project.

3.2 SUMMARY OF IMAGING TECHNIQUES

Table 3.1 contains an assessment of the comparative merits of the techniques that were trialled.

Capturing images through the microscope with the Canon 1000D digital camera was the best technique for this project. This technique produced the highest quality images in terms of sharpness and resolution. This technique was very efficient and convenient, due to the zoom and focusing features of the microscope. The mounted ring light on the microscope provided consistent lighting which enabled high reproducibility of the images.

	Flat-bed Scanner	Digital Photography					
		Bellows and Extension Tubes	Close-up Filter	Macro Lens	Lens coupling	Lens Reversing	Microscope Photography
Magnification[1]	Very poor	Good	Very Poor	Very poor	Good	Excellent	Excellent
Resolution – Pixels contained in a head[2]	429,025	1,807,674	107,910	N/A	2,007,853	2,958,400	5,607,424
Image Sharpness[1]	Poor	Poor	Poor	Medium	Medium	Good	Excellent
Ease of use[1]	Excellent	Medium	Excellent	Excellent	Poor	Excellent	Excellent
Cost	Low	Low	Low	Expensive	Low	Low	Low
Speed of Image Capture[1]	Poor	Medium	Excellent	Excellent	Medium	Excellent	Excellent
Consistency and Reproducibility[1]	Excellent	Poor	Excellent	Excellent	Very Poor	Good	Excellent

Table 3.1: An assessment of the comparative merits of each technique which was trialled for capturing images of the headstamps.

[1] The subjective scale used was Very poor, Poor, Medium, Good and Excellent

[2] The highest quality photograph produced by each method was used for this calculation. The photographs were cropped to a square which tightly encapsulated the head of the cartridge. Following this, Adobe Photoshop 7.0 was used to obtain the relevant number of pixels within the cropped image.

4 – METHODOLOGY FOR DATA COLLECTION

4.1 SELECTION OF THE SAMPLING RANGE

Prior to gathering boxes of ammunition for sampling, a relevant sampling range was determined. This was important as although CAC produced .22LR ammunition for 35 years between 1948 to 1983, the cartridges bearing the relevant sans-serif-ICI headstamp were only used for a limited period. Gracia and Walsh (2000) stated that cartridges bearing the sans-serif-ICI headstamp were used between 1960 and 1973. Upon gathering some boxes of ammunition, further observation showed that the sans-serif-ICI headstamp was first used around July 1959 but was not seen prominently until around July 1960 at around batch number 3400. Similarly, this headstamp was rarely seen after May 1971 at around batch number 5200. Consequently, the batch numbers focused on for this project spanned between 3400 and 5200. Understandably, this sampling range encompassed a very large number of different batch numbers (1800) and an extremely large number of boxes of ammunition (in excess of two million) [5].

The relevant batch number range also included some batches of ammunition that were not relevant to this project. The cartridges focused on in this project were .22LR cartridges which had a brass cartridge case and the sans-serif-ICI headstamp. The following ammunition types were able to be removed from the sampling range as these did not met the selection criteria:

- .22 Short cartridges (e.g. “ICI Short Non-rusting”).
- .22 Long Rifle High Speed Hollow Point Cartridges (characterised by nickel cartridge cases and the CAC Headstamp).
- .22 Long Rifle Shot ammunition.
- Boxes containing cartridges with copper cases (generally a characteristic seen in military ammunition with some exceptions).

Of the 1800 batch numbers which were focused on, approximately 180 were .22 Short rounds; 130 were .22 Long Rifle High Speed Hollow Point; 80 were .22 Long Rifle Shot and 140 had boxes containing copper-cased cartridges. This reduced the sampling range from 1800 different batch numbers to 1260.

4.2 COLLECTION OF AMMUNITION

Once the sampling range had been determined, a large number of CAC .22LR ammunition boxes that fell within the relevant sampling range were obtained. These boxes of ammunition were produced around 40 to 50 years ago so they were not available through usual retail outlets. The boxes of ammunition were gathered from Mr Kevan Walsh and Mr Kingsley Field, two established New Zealand cartridge collectors. Altogether about 280 boxes of ammunition were obtained. Some of the boxes obtained from Mr Field were from the original collection compiled and analysed by Dr Sprott during his studies on the sans-serif-ICI headstamp.

4.3 SELECTION OF BOXES FOR SAMPLING

Ideally, all of the boxes of ammunition would have been sampled however this was not possible for the following reasons:

- Some boxes were empty or contained very small numbers of cartridges.
- Some boxes were obviously not genuine and contained cartridges of mixed provenance.
- Time constraints associated with this project did not allow each box to be sampled, preferring instead to emphasize intra-box sampling.

The general guide to sampling the boxes of ammunition was as follows:

- Sample at least one box of ammunition from each shipment of cartridge cases received by CAC.
- Sample as many boxes of ammunition as possible around the time of the changeover from Pattern 8 bullets to Pattern 18/19 bullets (i.e. between batch numbers 3900-4100).
- For every 100 batch numbers sample at least six different batch numbers.

Obviously, these rules were subject to change from time to time depending on the availability of boxes of cartridges suitable for sampling.

The first step in selecting the boxes to be sampled involved assessing whether each box of ammunition contained cartridges of impure provenance (i.e. boxes containing cartridges which were not originally packed into the box by CAC). If a box containing non-original cartridges were to be unknowingly sampled, this could create substantial inaccuracies in the data collected.

In order to determine whether boxes contained a mix of cartridges, a visual analysis was carried out on the contents of each box. The main characteristics assessed included:

- Overall box contents – Cartridges should be consistent with the box description (e.g. cartridges within a box of "Long Rifle High Velocity Hollow Point" should not be loaded with solid bullets.
- Bullet type – In boxes where the vast majority of bullets were of a certain type (e.g. Pattern 8) and a small number of a different type (e.g. Pattern 18), this may indicate some cartridges of impure provenance. Additionally, the appearance of bullet types which were known to not have been in use during the time of production could indicate a mix (e.g. the appearance of a Pattern 19 bullet prior to the dates these were manufactured).
- Headstamp type – Mixes of headstamps within a box of cartridges could indicate a mix of cartridges. Also, the appearance of headstamps which were known to have been used in a different production period could indicate cartridges of impure provenance.
- Case type – The main cartridge case types used at CAC in .22LR ammunition were brass, copper and nickel. A box containing a mix of the different case types would be indicative of a mix of cartridges.

Importantly, some original boxes of ammunition were known to contain cartridges with mixed characteristic (e.g. mixed bullet types or headstamp types). This was a relatively rare event and most likely occurred from the mixing of cartridges during the manufacturing processes. This made it important to consider whether boxes could have been genuine when cartridges of mixed characteristics were found.

In instances where the contents of a particular box of cartridges were identified as being of impure provenance, the box was usually omitted from further sampling. However, the presence of cartridges of impure provenance did not necessarily rule boxes out of sampling, providing the majority of the cartridges appeared to be genuine and there was only a localised minority of impure cartridges. This was particularly important for boxes of ammunition where there was a lack of other boxes available from the same production period. Although boxes of suspected impurity were generally avoided when these were used the severity of the mix was noted and the cartridges of likely impure origin were removed from sampling. This was problematic as sampling such boxes could have caused error in the data collected from the headstamps.

However, this risk was deemed necessary in order to ensure the sampling covered a wide range of batch numbers.

Where boxes of ammunition contained less than 30 cartridges, these boxes were usually omitted from sampling.

The procedure of selecting the appropriate boxes yielded 117 boxes of ammunition for further sampling and data collection.

It is important to emphasize that stringent measures were taken in an attempt to minimise the sampling of cartridges of impure provenance. However, it was still likely that some impure cartridges were not detected and may have been sampled. Due to the nature of sampling 40 to 50 year old ammunition this situation was unavoidable. This could have led to the production of some flawed results and hence this was an important factor to consider when assessing the results from the data collected.

4.4 SAMPLING PROCEDURE

Prior to the sampling of cartridges from each box, the entire box contents were inspected for interesting features. Such features included the general condition of the headstamps (e.g. corrosion and bunter wear), unusual markings on the cartridge cases, incomplete headstamp impressions and headstamp impression depth. Where interesting features were found these were noted.

Within a full box of CAC .22LR ammunition there are 50 cartridges, tightly aligned in five rows and ten columns. The cartridges are orientated in such a way that there are 25 cartridges with their heads facing upwards and 25 with their heads facing downwards. In order to substantially reduce the time spent when removing and re-packing cartridges, the sampling was limited to the cartridges with their heads facing upwards. The cartridges with their heads facing upwards were assigned numbers from 1 to 25 (Figure 4.1). Additionally, the side of the box was lightly marked with a pencil to orient the box.

Figure 4.1: A full box of ICI .22LR ammunition showing the assigned numbering of the cartridges.

To avoid systematic errors in sampling, a random number generator was used to select ten cartridges from each box of ammunition. The random numbers were produced in Microsoft Excel where the following formula was used to randomly generate an integer between 1 and 25 inclusive.

=INT(RAND()*25) + 1

The random numbers produced were used to select ten cartridges from each box (according to the numbering scheme in Figure 4.1) with duplicate numbers ignored. As each cartridge was selected it was removed from the box and the appropriate number was marked on the side of the cartridge case. This number would become the cartridge's "sample number". Additionally, a small dot was placed on the head of the cartridge to assist in quick identification of the sampled cartridges within each box if required at a later date. An example of these markings is shown in Figure 4.2.

Some of the ammunition boxes that were used were not full and therefore did not contain the cartridges in the usual orientation (cartridges were loose within the box). The exact number of cartridges within these boxes was recorded. Subsequently, the random number generator was altered to accommodate the reduced number of cartridges.

Figure 4.2: Photographs demonstrating the numbering and marking of the sampled cartridges. Left: A cartridge with a sample number marked on its cartridge case. Right: A small dot placed on the head of a cartridge to indicate it has been sampled.

Problematic cartridges were often encountered during sampling. An example of a problematic cartridge is one that has been subject to substantial corrosion or other eroding processes causing problems when visualising the headstamp. When these cartridges were selected by the random sampling technique they were assessed and if the headstamp was deemed to be too problematic for further analysis it was ignored and another cartridge was selected.

4.5 INITIAL EXAMINATION OF CARTRIDGES

The ten cartridges selected from each box underwent a brief examination prior to photographing.

The rims of the cartridges were examined under a stereo microscope in order to determine the primed state of the cartridges (see 2.3.4). If any special features on the rim were present, or if determining the primed state of the cartridge was ambiguous, this was recorded.

The diameter of the head of each cartridge was measured using digital callipers in order to assist in scaling the images during data collection (see 4.8.1). The heads of the cartridges were rarely perfectly circular in shape due to the nature of rim formation during cartridge case manufacture. For this reason, two orthogonal diameter measurements were made for each cartridge. If the head of the cartridge were to be positioned so that the “ICI” lettering was upright (reading from left to right), one measurement was made across the horizontal face of the cartridge, with the other measurement made across the vertical face of the cartridge.

Additionally, the type of bullet which was loaded into each cartridge was recorded. Determining the type of bullet was performed by visually analysing the shape, number of cannelures and whether the bullet was hollow-point or solid (see 2.6.3).

4.6 CAPTURING IMAGES

The photographs of the headstamps were captured with a Canon 1000D digital camera attached to a Leica MZ6 bench microscope via a trinocular intermediate tube (see Chapter 3). The cartridges were held in a cartridge stand so that the heads of the cartridges were facing upwards (Figure 4.3). The headstamps were magnified sufficiently using the adjustable magnification of the microscope. The lighting was provided by the Leica CLS 150X ring light which was mounted onto the microscope. The film speed used was ISO200. The exposure time for the photographs was optimized (usually in the range of 1/60th to 1/200th of a second) and the photographs were collected with the appropriate photograph numbers recorded. In most instances multiple photographs were captured for each headstamp.

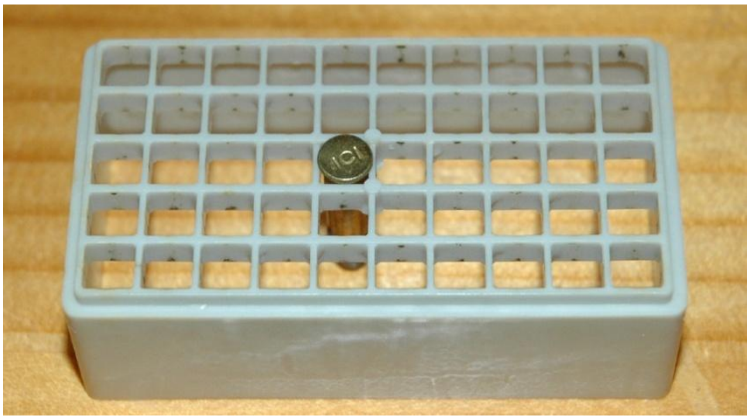


Figure 4.3: A cartridge sitting in the cartridge stand that was used for the photographs.

4.7 GEOMETRIC PROCESSING OF IMAGES

Image processing and data collection were the most time-consuming and work-intensive steps involved in the analysis of the headstamps. Processing and collecting data from all ten photographed headstamps was not practical so only six of the headstamps were selected to be processed. There were occasional exceptions to this rule where interesting boxes were encountered and all ten of the photographed headstamps were processed. When selecting six headstamps from the ten photographed, this was usually done randomly however in some instances several headstamps could be excluded from further processing due to obscured edges or lack of contrast between the headstamp and the head. Removing these headstamps reduced the error of the data collected. The headstamps with severely obscured edges were generally removed from sampling at an earlier stage, however often small irregularities in the edges were not detected until the headstamps were viewed under sufficient magnification.

Geometric processing of images was performed to facilitate the formation of data points, for which the coordinates were collected in a subsequent step (see 4.8). The same geometric processing procedure was performed on each headstamp.

The geometric processing procedure can be broken into seven sequential steps. The entire procedure was carried out in "Adobe Photoshop 7.0". In order to assist the geometric processing procedure, a custom shape was designed in Adobe Photoshop (Figure 4.4). The custom shape was formed on a blank sheet using the pre-set shapes available. This involved drawing a square followed by fitting a circle within the square. Next, lines were drawn horizontally and vertically through the centre of the square in order to produce the "cross-hair" which was used to show the centre of the shape. This shape will be referred to from this point as the "cross-hair shape".

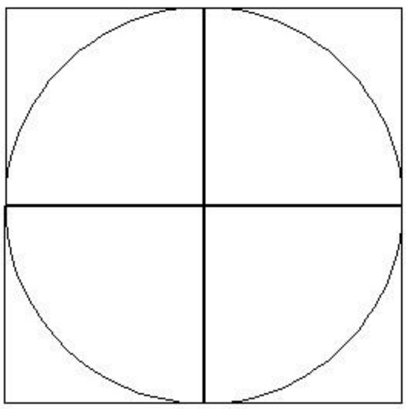


Figure 4.4: The "cross-hair shape", composed of a square, a circle and a cross-hair.

4.7.1 Initial Straightening of Images

The first step of geometric processing involved an initial straightening of the image, so that the "ICI" headstamp read from left to right. This was performed using the "Measure tool" to draw a line down one of the straight edges of the left "I". The "Measure tool" was used to measure the angle at which the headstamp was misaligned. This was subsequently corrected by rotating the image by the degree of misalignment (Figure 4.5). This was performed as a crude straightening of the images in order to simplify and increase the accuracy of the subsequent steps. The images were subject to a more precise straightening at a later stage of processing (see 4.7.4).

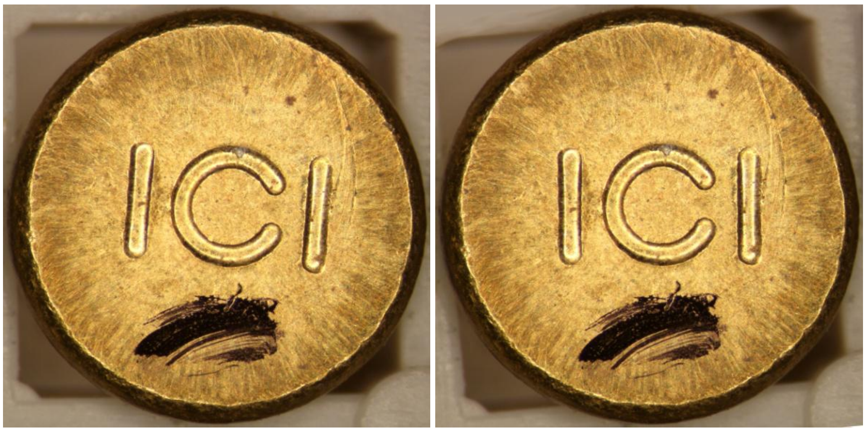


Figure 4.5: The initial straightening of the images. Left: The initial image of a headstamp as photographed. Right: the image of the headstamp after the initial straightening step.

4.7.2 Formation of the End-Points of the Left and Right "I" Skeletal Lines

During manufacture, a cutting tool rotates to form the impression left in the hob, which eventually becomes reproduced in the headstamps (see 2.4.1) [2]. This leads to semicircular impressions left at the ends of each of the letters. The centre of the semicircular impressions represents the end points of the skeletal lines of the letters.

By fitting the cross-hair shape to the ends of the left "I" and right "I", the end points of the skeletal lines of these letters were able to be determined. The cross-hair shape was sized using the relative thickness of the lettering as a guide (Figure 4.6). After sizing, the cross-hair shape was fitted to the ends of the "I"s by what was perceived to be the best fit (Figure 4.7). Following this, the "Stroke path" tool was used to fill the outline of the shape with a one pixel wide black line (Figure 4.8). Up until this point the shape only existed as a "path" in the image and was transparent. The "Stroke path" tool causes the "path" to be outlined with a raster stroke, making it visible on the image. The "Stroke path" step was repeated for all the subsequent shapes and lines that were drawn on the images and will not be mentioned again from here forward.

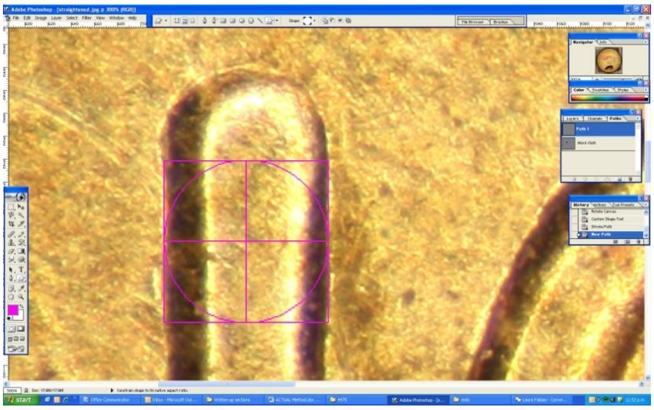


Figure 4.6: Screenshot from Adobe Photoshop showing the sizing of the cross-hair shape using the thickness of the letter as a guide.

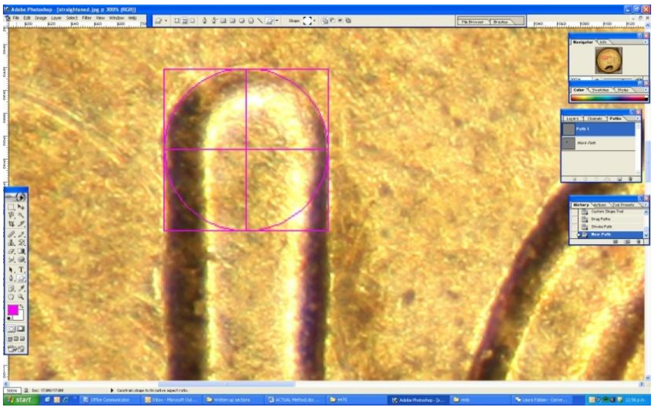


Figure 4.7: Screenshot from Adobe Photoshop showing the cross-hair shape after being moved to the top of the left "I".

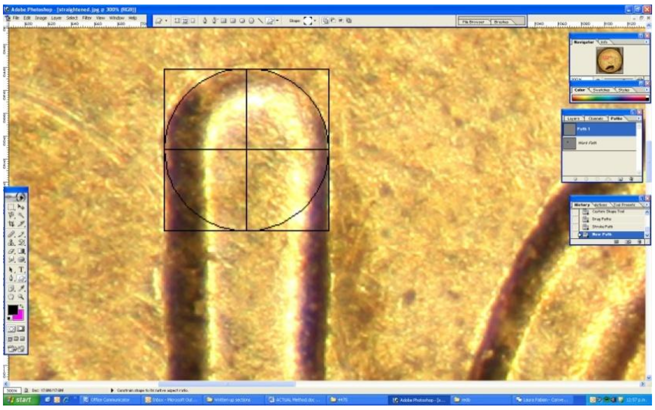


Figure 4.8: Screenshot from Adobe Photoshop showing the cross-hair shape after the shape had been outlined with a one pixel wide raster stroke.

Fitting the cross-hair shapes to the ends of the "I"s proved problematic at times due to the irregular edges at the ends of some of the letters. In order to deal with these types of headstamps consistently, the cross-hair shape was fitted to the end of the letter so that the middle of the shape's leading semicircle was against the edge of the letter. An example can be seen in Figure

4.9, where the arrow shows the middle of the shape's leading semicircle pressed against the edge of lettering.

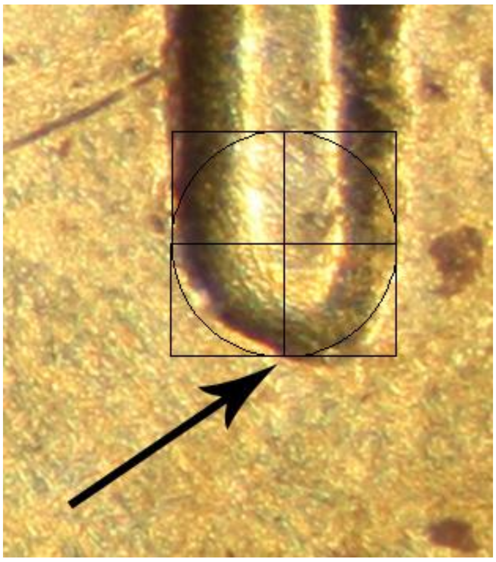


Figure 4.9: Screenshot from Adobe Photoshop showing how the letters with irregular edges were dealt with during geometric processing. The arrow shows the middle of the leading semicircle of the cross-hair shape touching the irregular edge of the lettering.

An example of the resulting headstamp after insertion of the cross-hair shape to the ends of the "I"s is shown in Figure 4.10. The various shapes in position have been labelled A to D.

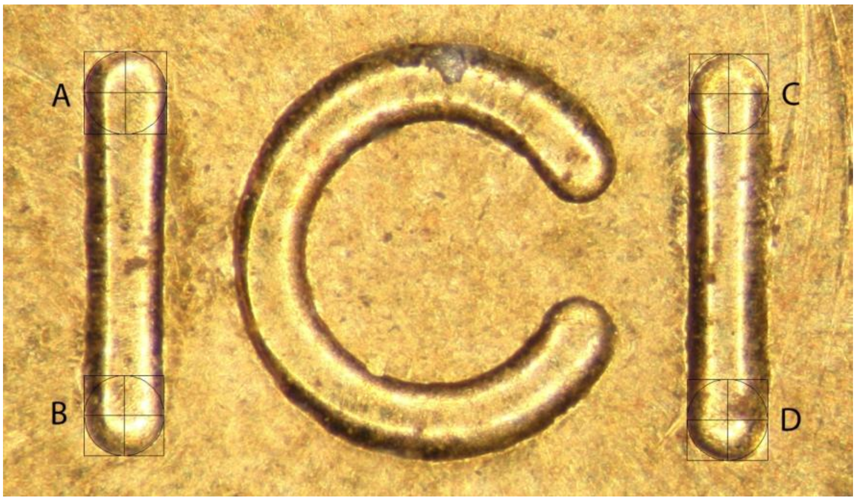


Figure 4.10: Image showing the headstamp with the cross-hair shapes (A, B, C, D) inserted into the ends of the "I"s.

4.7.3 Drawing the Skeletal Lines of the Left and Right "I"

The "Pen tool" was used to draw a line between the centre of shape A and the centre of shape B to produce the skeletal line of the left "I". Similarly, the skeletal line of the right "I" was formed by drawing a line between the centre of shape C and the centre of shape D. Additional diagonal lines were drawn from the centre of shape A to the centre of shape D and from the centre of shape B to the centre of shape C. These diagonals served as a means to show the true centre of the headstamp as the lines intersected at a middle point between the left and right “I”s. An example of the image produced after this step is shown in Figure 4.11.

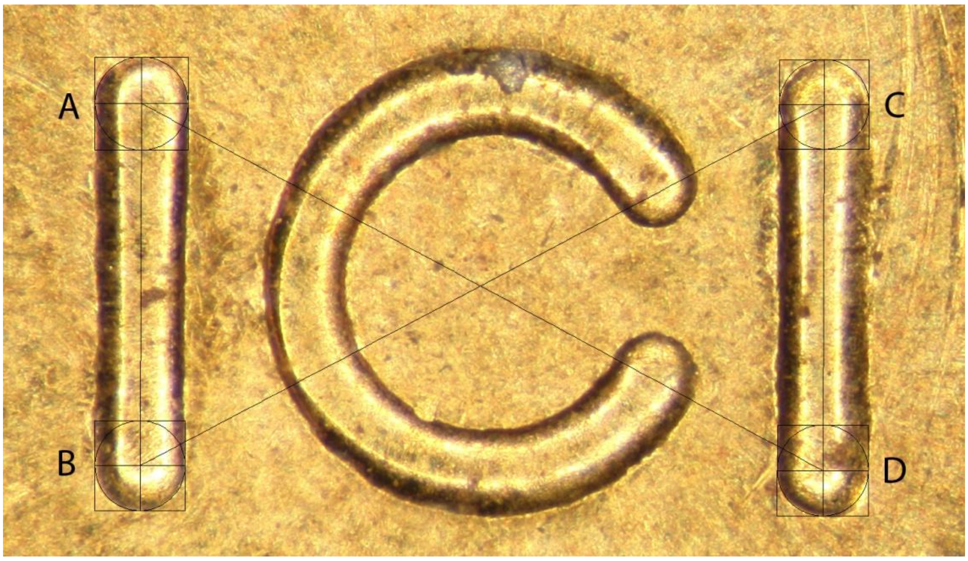


Figure 4.11: An image showing the headstamp after the skeletal lines of the “I”s and the diagonals had been added.

4.7.4 Precise Straightening of Images

Prior to further processing, the images were precisely straightened in order to standardise all the images in their orientation. Failing to have all the images in the same orientation would lead to flawed data. The “Measure tool” again was used (see 4.7.1) with the skeletal line of the left “I” being used as a guide. This resulted in images where the skeletal line of the left “I” was exactly vertical.

4.7.5 Producing the Skeletal Line of the “C”

In order to create the end points of the skeletal line of the “C”, the cross-hair shape was fitted to the ends (horns) of the “C”. This was done in the same manner as performed for the ends of the “I”s (see 4.7.2). The cross-hair shapes will be referred to as shape E in the upper horn and shape F in the lower horn (Figure 4.12). In order to fit the skeletal line of the “C”, the circle of the cross-hair shape was used. It was acceptable to use a circle to fit the skeletal line of the “C” as during production of the hobs the letter “C” was formed as an uncompleted circle [2]. The cross-hair shape which was used to fit the skeletal line of the “C” will be referred to as shape G (Figure

4.13). To guide the fitting of the skeletal line of the “C”, four temporary cross-hair shapes were fitted within the lettering of the “C” (Figure 4.12).

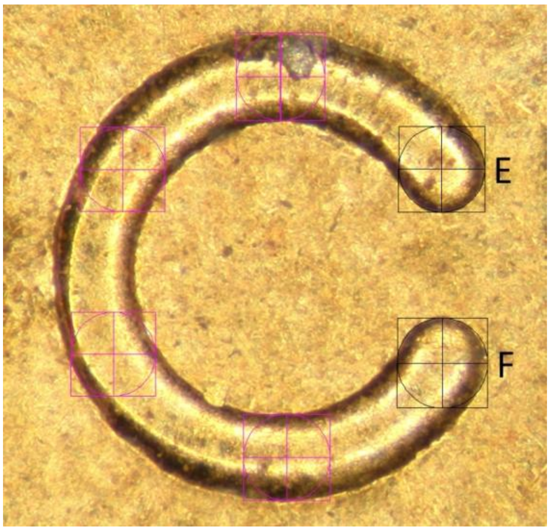


Figure 4.12: Shapes E and F fitted into the upper and lower horns of the “C”. Four additional temporary cross-hair shapes (red) can be seen within the lettering of the “C”.

Shape G was then fitted to the “C” so that the circle (of shape G) passed through the centre of the four temporary shapes and shape E and F. It was often difficult to fit shape G so that the circle passed through the exact centre of each guide shape (probably a result of uneven bunter wear), so the best fit was used. After shape G had been fitted to the “C”, the temporary custom shapes were deleted, leaving shapes E, F and G (Figure 4.13). In addition to showing the skeletal line of the “C”, shape G also served to show the centre of the “C” in the middle of the cross-hair.

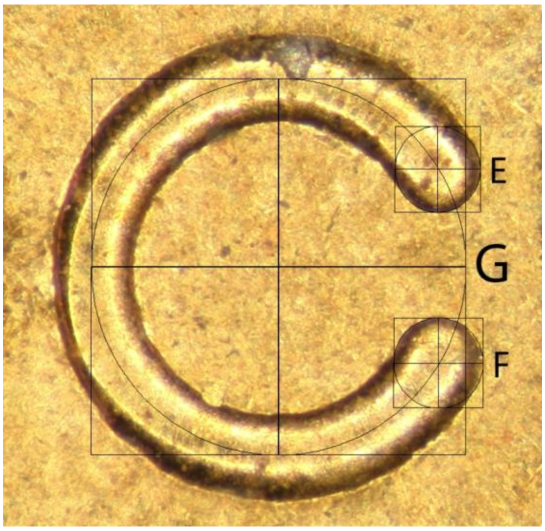


Figure 4.13: Shapes E and F fitted to the horns of the “C”, with the larger shape G producing the skeletal line and the middle of the “C”.

4.7.6 Extension of Shape G

As an extension to the previous step, the horizontal midline of shape G was extended in both directions so that it reached past both edges of the “I”s. This was performed using the “Pen tool”. The drawing of this line created a consistent midline which passed through the skeletal lines of both “I”s. This line was used during data collection to assist with the collection of coordinates relating to the thickness of the letters (Figure 4.14).

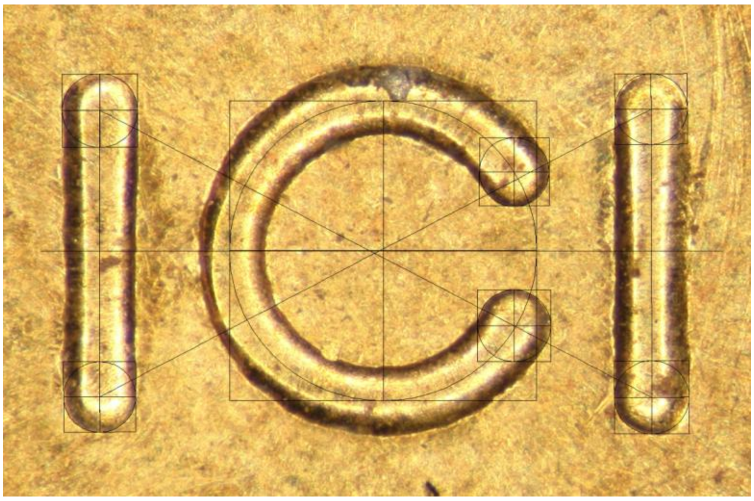


Figure 4.14: A headstamp prior to the final step of geometric processing

4.7.7 Finding the Centre of the Head of the Cartridge

The headstamps were not always positioned in the centre of the head of the cartridge. For this reason it was seen as important to create a data point which showed the middle of the head of the cartridge relative to where the headstamp was positioned. To do this, another cross-hair shape (shape H) was produced which was fitted around the head of the cartridge so that the circle of shape H encompassed the circumference of the head (Figure 4.15). Fitting shape H to the head of the cartridges proved difficult at times as the heads of the cartridges were rarely perfectly circular, so a best fit was applied.

Figure 4.15: A cartridge with shape H fitted around the head in order to define the middle of the head (to help visualise this shape, the lines have been adjusted from one to nine pixels thick).

Finally, the images were cropped to remove the irrelevant background of the images. An example of an image after geometric processing is shown in Figure 4.16.

Figure 4.16: An example of a headstamp after geometric processing. The shapes have been thickened from one pixel to five pixels wide.

4.8 DATA COLLECTION

The data for this project was collected in the form of Cartesian coordinates. The programme used for data collection was “Grab It! XP” which is a Microsoft Excel-based programme.

Data collection using Grab It! XP can be divided into three steps: Image Upload and Scaling; Collection of Coordinates; and Exporting the Collected Data.

4.8.1 Image Upload and Scaling

The first step of data collection involved uploading the desired geometrically processed image. The general size of the images after image processing was around 2 megabytes with dimensions of around 2500 pixels by 2500 pixels.

Before data was collected the image was scaled. This was done by selecting the “x-axis origin”, “x-axis maximum”, “y-axis origin” and “y-axis maximum” as shown in Figure 4.17. This essentially resulted in the x and y axes been positioned as shown in Figure 4.18.

Following determination of the axes, the appropriate values were inserted to facilitate scaling of the image. For the x and y axes minimums a value of zero was used. The values (mm) for the x and y axes maximums were taken directly from the diameter measurements of the head of the cartridges (see 4.5).

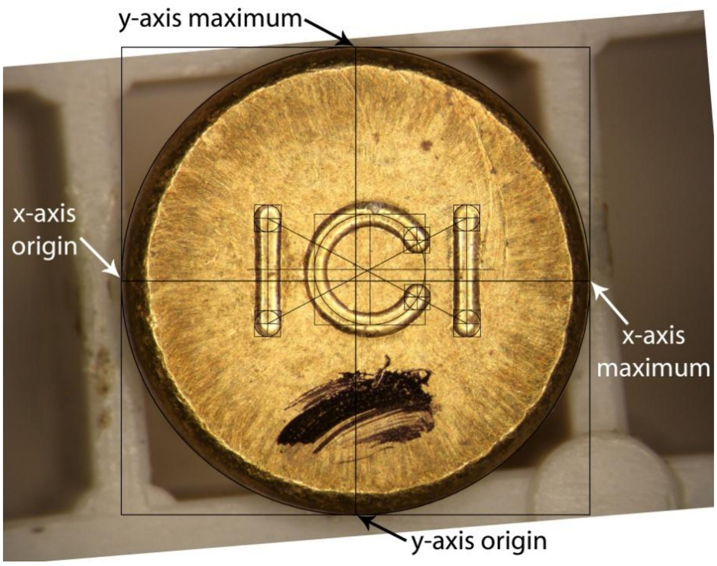


Figure 4.17: A geometrically processed image showing the various parameters of the axes.

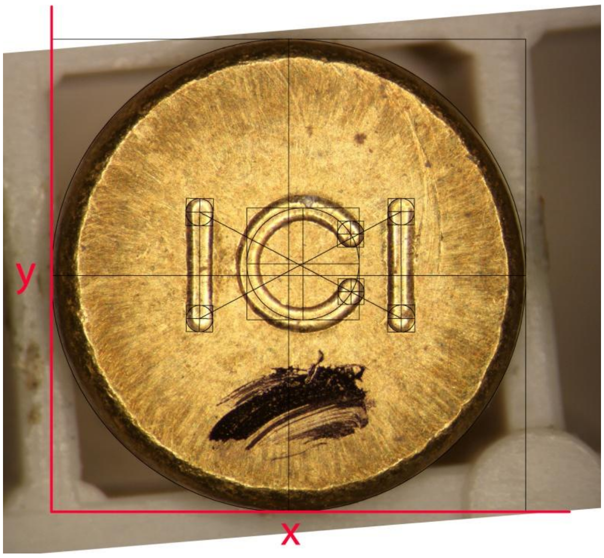


Figure 4.18: A geometrically processed image showing the theoretical position of the x and y axes (red) after determining the axes in Grab It! XP.

4.8.2 Collection of Coordinates

In Grab It! XP the coordinates of specific points on an image can be collected by positioning the cursor over the desired point and pressing the left mouse button. The output from the data collection is displayed in real time as the coordinates are gathered. The relevant data points which were used for collection had been produced on each headstamp during the geometric processing procedure in Adobe Photoshop (see 4.7). A screenshot from Grab It! XP is shown in Figure 4.19. For each headstamp the coordinates of 22 data points were collected. The 22 different data points have been labelled and are shown in Figures 4.20 to 4.22.

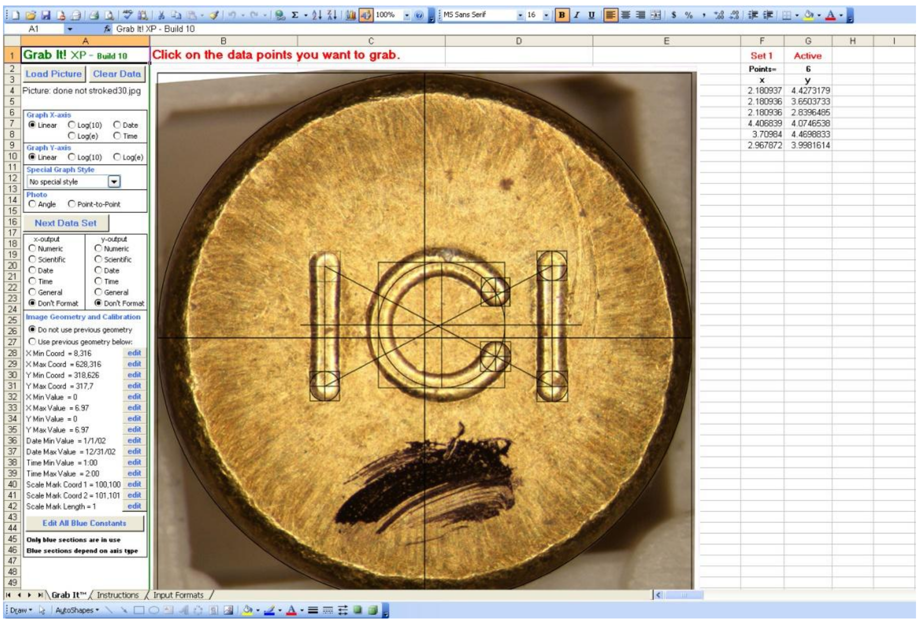


Figure 4.19: Screenshot from Grab It! XP showing six collected coordinates (top right).

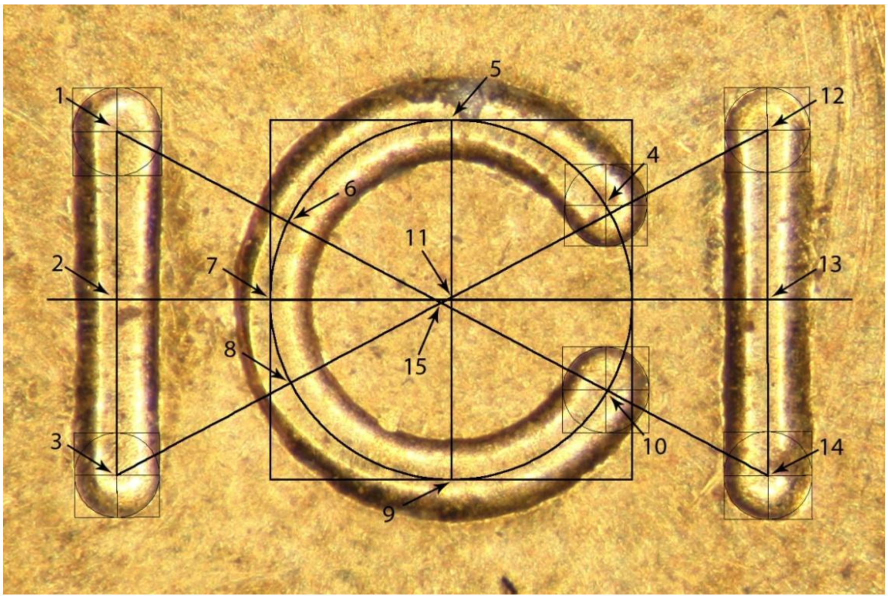


Figure 4.20: Image showing data points 1 to 15.

The data points labelled 1 to 10 and 12 to 14 reside within the lettering of the skeletal lines of the lettering within the headstamp. Data point 11 represents the centre of the "C" and data point 15 represents the centre of the headstamp (the centre-point between the left "I" and right "I"). Data point 16 (Figure 4.21) represents the centre of the head of the cartridge.

Figure 4.21: Image showing data point 16.

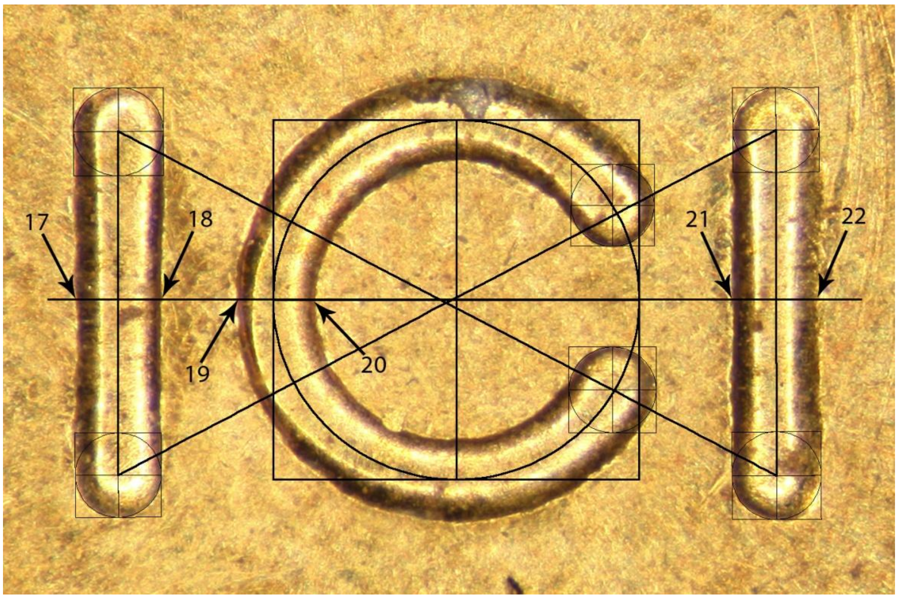


Figure 4.22: Image showing data points 17 to 22.

Data points 17 to 22 reside along the horizontal line which was extended from shape G (see 4.7.6). The data points were taken where this line crossed the edges of the lettering.

4.8.3 Exporting the Collected Data

Grab It! XP is a Microsoft Excel based programme so the collected coordinates were produced in a Microsoft Excel format. Following data collection, the 22 different coordinates were copied from Grab it! XP and transferred to an appropriate Microsoft Excel worksheet for transformation and analysis of the data.

4.9 TRANSFORMATION OF DATA

4.9.1 Standardising the Data

Prior to performing statistical analyses on the data it was essential to standardise the data. When considering how the axes were positioned during data collection (Figure 4.18), it was important to realise that the relative position of the headstamp within the head of the cartridge had a large effect on the data collected from each headstamp. For instance, the headstamps shown in Figure 4.23 are identical. As the headstamps are identical, one would expect the data collected from each headstamp to be identical except for some minor experimental error. However, there is a difference in the position of the headstamps within the head of the cartridges. The headstamp on cartridge B is located slightly higher and to the right of where the headstamp on cartridge A is located. The difference in headstamp position causes a substantial difference between the coordinate data collected from each cartridge.

Figure 4.23: Photographs of two cartridges bearing identical headstamps. The position of the headstamp on cartridge A differs to that of cartridge B.

The problem caused by the positioning of the headstamps within the heads of the cartridges was remedied by transforming the data so that there was a common point between all of the headstamps.

The data collected from each headstamp was transformed so that data point 3 (Figure 4.20, the bottom of the skeletal line of the left "I") became the origin of the axes. This was done by subtracting the coordinates collected for data point 3 (3x, 3y) from all the other gathered coordinates. This transformation will be referred to as the "standardising transformation".

For instance, the standardising transformation for data point 1 (1x, 1y) would be (1x – 3x , 1y - 3y).

Data point 3 (the bottom of the skeletal line of the left "I") was seen as the logical choice to become the origin of the axes for the standardised data because the images had been previously straightened to make the skeletal line of the left "I" vertical. This effectively meant that the bottom of the skeletal line of the left "I" became the origin of the axes with the rest of the skeletal line of the left "I" lying on the y axis.

4.9.2 Restructuring the Data

Following the initial standardising transformation, the data was rearranged to prepare the data for further working and statistical analysis. The coordinate data collected from Grab It! XP was arranged in a table containing two columns (x and y) and 22 rows (one for each data point). This same structure had been retained after the standardising transformation. This structure was unacceptable to present large amounts of gathered data and did not allow easy manipulation of the data. Furthermore, this data structure was not compatible for use with the statistical programme “R”.

The structure of the data was altered so that the coordinates collected from each headstamp were arranged into a single row of information, with the addition of the relevant batch number and sample number for each headstamp.

For instance, the theoretical data from Batch 4500, Sample 15 was originally recorded as follows;

Batch 4500 – Sample 15

x	y
1x	1y
2x	2y
3x	3y
4x	4y
5x	5y
6x	6y

This was rearranged to the following format;

4500	15	1x	1y	2x	2y	3x	3y	4x	4y	5x	5y	6x	6y

4.9.3 Calculating Data Transformations

Following rearrangement of the data, some coordinates were used to measure the distance or relationship between various points of interest. The use of the standardised coordinates to produce distance or relationship measures will be referred to as “data transformations”.

The measured parameters which were originally used for the various analyses at the 1980 Royal Commission were used as a guide for which data transformations were calculated (see 1.1.4). This was performed as a means to replicate the original work done on the headstamps. Some additional data transformations that had not been used in the previous analyses were also calculated.

The concepts behind some of the parameters used by Dr Sprott and Professor Mowbray were inspired by the original parameters used by Mr McDonald. The difference that existed between these lies in the method used to measure the parameters, namely whether the skeletal lines of the letters were used. Mr McDonald did not use the skeletal lines of the letters and therefore all measurements were made from the relevant edges of the letters. Conversely, Dr Sprott and Professor Mowbray decided that measurements from the skeletal lines would be more accurate as these are not subject to wear or differences in the cutting tool used to engrave the hob.

Table 4.1 contains a list of the data transformations which were calculated for each headstamp, along with the relevant standardised coordinates used and the calculations. The numbers refer to the data points (Figures 4.20-4.22), where x or y denotes the x coordinate or the y coordinate of the relevant data point. The data transformations have also been attributed to the original work done for the 1980 Royal Commission of Inquiry.

Data Transformation	Calculation	Attributed to
Left “I” Skeletal Height	1y – 3y	
“C” Skeletal Height	5y – 9y	
Right “I” Skeletal Height	12y -14y	
Sum of Letter Skeletal Heights	(1y – 3y) + (5y – 9y) + (12y -14y)	McDonald*, Sprott & Mowbray
Headstamp Skeletal Width	13x – 2x	McDonald**, Sprott & Mowbray
Width of Left “I”	18x – 17x	McDonald
Width of “C”	20x – 19x	
With of Right “I”	22x – 21x	McDonald
Sum of Letter Widths	(18x – 17x) + (20x – 19x) + (22x-21x)	
I-C distance 1 (Skeleton of Left “I” to Middle of “C”)	11x – 2x	Sprott & Mowbray
I-C distance 2 (Edge of Left “I” to Edge of “C”)	19x – 18x	McDonald
I-C distance 3 (Skeleton of Left “I” to Skeleton of “C”)	7x – 2x	
C-I distance 1 (Middle of “C” to Skeleton of Right “I”)	13x – 11x	Sprott & Mowbray
C-I distance 2 (Edge of “C” to Edge of Right “I”)	21x – 20x	McDonald
C-I distance 3 (“C” Skeleton to Skeleton of Right “I”)	13x – 7x	
Horn Distance	4y – 10y	McDonald
Horn Angle	(see below)	Sprott & Mowbray

Table 4.1: The various data transformations which were calculated for this project.
* The concept behind measuring the letter heights was proposed by Mr McDonald where the actual letter heights were measured and summed. This was then altered by Dr Sprott and Professor Mowbray who measured the letter heights from the skeletal lines and summed the heights together.
** The width of the headstamp was originally used by Mr McDonald. In his analysis, Mr McDonald presumably measured from the outside edge of the left “I” to the outside edge of the right “I”, a measurement he referred to as “I-C-I overall width”. This was altered by Dr Sprott and Professor Mowbray where the distance between the skeletal line of the left “I” and the skeletal line of the right “I” was used.

Calculation of the horn angle was slightly more complex than the other transformations. For this calculation, the coordinates were used to create two right angle triangles and then trigonometry was used to calculate the resulting angles (Q and R) which were added together (Figures 4.24 and 4.25).

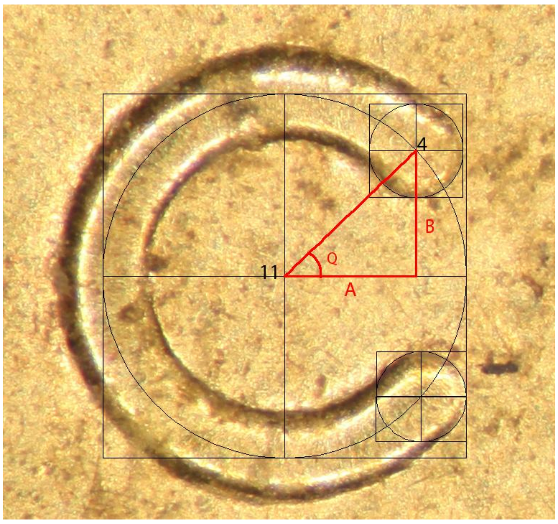


Figure 4.24: Image showing how angle Q was calculated for measuring the horn angle.

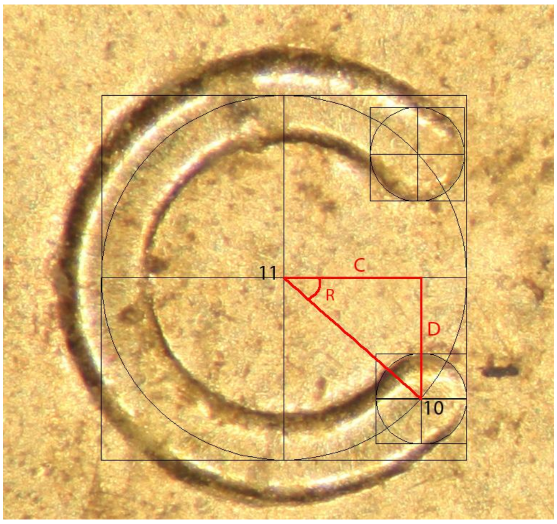


Figure 4.25: Image showing how angle R was calculated for measuring the horn angle.

Horn angle = Q + R

$$= \tan^{-1}(B/A) + \tan^{-1}(D/C)$$

Where:

A = 4x – 11x

B = 4y – 11y

C = 10x – 11x

D = 11y – 10y

Due to the nature of the positioning of the horns of the letter "C", the distances denoted by A and C were not necessarily equal. Similarly, the distances denoted by B and D were not necessarily equal. This made it necessary to calculate Q and R independently when calculating the horn angle. Calculating just Q or R and doubling the result would have resulted in an incorrect measurement of horn angle.

Further standardised coordinates that were not subject to calculations (data transformations) were also used for statistical analysis. These were as follows.

- Centre of the headstamp = (15x, 15y).
- Centre of the head relative to headstamp = (16x, 16y).
- Horizontal diameter of head = (see 4.5).
- Vertical diameter of head = (see 4.5).

5 – MULTIVARIATE STATISTICAL TECHNIQUES

The collected data for this project was analysed using various statistical techniques. In any analysis, no single statistical technique will answer all the questions. Therefore, it is important to explore different approaches. The statistical techniques used to analyse data in this project included Principal Components Analysis, Hierarchical Clustering and Linear Discriminate Analysis.

For this project, all of these statistical techniques were performed using the statistical programme "R" [31]. R is a freely available and extremely powerful statistical programme capable of performing a wide variety of statistical data analysis.

This section gives some background to the statistical techniques used in this project.

5.1 PRINCIPAL COMPONENTS ANALYSIS

Principal components analysis (PCA) is a useful statistical technique which has found application across many different fields. It is commonly used in exploratory data analysis to assist in visualising high dimensional data sets which would otherwise be problematic due to the multivariate nature of the data. The main purpose of PCA is to reduce the number of variables in order to assist in visualising the relationships in the data [32]. In essence, PCA uses fewer components to represent the original variables and thus consolidates the data for easy interpretation [33].

PCA works by taking linear combinations from the set of original variables to derive a new set of variables which explain the maximal variance in the data [34, p80]. The number of linear combinations, or "principal components", equals the number of original variables therefore no information is lost [33]. By transforming the original variables to the same number of components it would appear PCA in its raw form does not effectively reduce the dimensionality of the data. However, the components derived from PCA have two important and useful properties. Firstly, the derived components are independent of one another [34, p80]. Secondly, the derived components describe a decreasing amount of variability in the original data. That is, the components are ordered in such a way that the first principal component describes the largest sample variation, the second component describes the second largest and so on. As a consequence of this the first and second principal components cumulatively describe the majority of the variability in the data. It is this property that can be exploited for dimension reduction. One can discard the less important components and keep only the first few components to achieve effective dimension reduction [33]. In this way, PCA is usually visualised by producing a biplot of principal component 1 versus principal component 2 (PCA biplot) in order to show most of the patterns that exist within the data [34, p80]. A simplified demonstration of the use of PCA has been described by Campbell (see [34, p81]).

5.2 HIERARCHICAL CLUSTERING ANALYSIS

Hierarchical clustering is a type of cluster analysis. Cluster analysis refers to a broad group of multivariate techniques whose primary purpose is to group observations based on the characteristics they possess [35, p423]. Cluster analysis looks to classify observations so that each observation is very similar to the other observations in the same cluster. The resulting clusters should then exhibit high homogeneity within each cluster and high heterogeneity between clusters. When calculating the similarity between observations, a range of distance measures can be employed, such as Euclidean distance [35, p430].

Hierarchical clustering involves creating a hierarchy of clusters which can be represented in a tree structure known as a dendrogram [35, p438]. There are two main types of hierarchical clustering procedures known as "agglomerative" and "divisive" [35, p437]. Agglomerative methods start with each observation as its own cluster. In the subsequent steps, the two closest related clusters are combined into a new aggregate cluster leading to the reduction of the number of clusters at each step in the tree. Eventually, all of the clusters become grouped into one large cluster. The divisive method of hierarchical clustering proceeds in the opposite direction to that of agglomerative methods. The divisive method begins with one large cluster containing all of the observations with the successive steps leading to observations that are dissimilar splitting off and being made into smaller clusters. This process continues until each object is a cluster in itself.

When examining a dendrogram, the relationships between the observations can be determined by examining the structure of the tree and looking for clusters of similar observations.

5.3 LINEAR DISCRIMINATE ANALYSIS

Linear Discriminate analysis (LDA) is similar to PCA as both look to produce linear combinations of variables which best explain the data. LDA looks to construct a new set of "linear discriminates" that best separate data into known groups [34, p84].

LDA is a supervised learning method. This means that it requires a user's prior knowledge of the grouping (class) of a given object in the data set in order to build the rules for separating the observations into groups [34, p84]]. With regard to this project, this means LDA takes into account the batch numbers of the data and the rules for the analysis are produced in order to try and group the observations with the same batch number into the same group and the observations with different batch numbers into different groups. Separation is achieved by maximising the ratio:

$$\frac{\text{Between-group variance}}{\text{Within-group variance}}$$

In other words, LDA looks to maximise the differences between groups and to minimise the differences within groups [36]. The ability of LDA to maximise group differences and determine which variables are contributing to the inter-group differences is a desirable feature [34, p85]. PCA differs to LDA in this sense as PCA is an unsupervised method. This means the groups (class) do not have to be specified for the analysis. In other words, in PCA the batch numbers of the observations are not used to help model the data. Instead, the data is grouped according to similarities and differences in the variables between the observations.

When referring to LDA, the first linear discriminate is that which describes the largest amount of inter-group variance [34, p85]. The second linear discriminate describes the next largest amount of inter-group variance, and so on. In this way LDA can also be used for dimension reduction in the same way as for PCA.

LDA also has classification functions which can be used to classify new unknown data. This is a useful function particularly in a forensic setting where the "source" of an object is in dispute [34, p84]. This allows for the allocation of new specimens into a database of specimens of known origin. In the context of this project, a classification model can be built from the data collected from headstamps of known origin. Following this, the model can be used to predict the most likely batch of origin for data which has been collected from a headstamp of unknown origin.

The error rates of the classification model can also be assessed using a cross-validation method [34, p85]. The most basic form of cross-validation is known as the "hold-out" method. In this method a portion (e.g. one third) of the original data is held back from the LDA model building process (the testing set). The remaining data (e.g. two thirds) can then be used to build the classification model (the training set). After the model has been produced, the testing set can be introduced to the model as unknown data and the model can be used to provide predictions of the most likely origin of the data. By doing this the predictions can be used to assess the accuracy of the classification model. However, there are problems with only using a portion of the data for building the model. Firstly, the training and/or testing set of the model might not be representative (e.g. a class of data may not be represented at all in the training set, therefore no classifier for this class would be learnt). Additionally, the random set of data in the training set may not be very representative of each class. This can be remedied by allocating a set proportion of the samples from each class (e.g. batch) into the training set. Also, the cross-validation of the data can be repeated a number of times with the results from the predictions averaged (see 7.1.3.2).

6 – DATA EXPLORATION

All data analysis should begin with attempts to visualise the data in a meaningful manner [34, p70]. This process is known as exploratory data analysis. It is essential to be able to visualise the data on a basic level before employing the use of advanced statistical techniques. Exploratory data analysis techniques, such as PCA, are useful for visualising data when it is multivariate in nature, since it is very difficult to understand the data by looking at a large matrix.

PCA was the main exploratory data analysis tool used in this project, where the dimension reduction properties were exploited. The results from the principal component analyses were presented as a plot of principal component 1 versus principal component 2. These biplots were used throughout the data exploration and subsequent statistical analysis. It is important to establish some background as to how to interpret the biplots. The pairs of biplots presented in Figure 6.1 will be used as an example. The labels in the top biplot and the coloured dots in the bottom biplot, refer to where the observations are placed within the two-dimensional reduced space of the PCA biplot. The labelling (top) includes the relevant batch number and sample number of each observation. In the bottom biplot, each batch number has been assigned a different colour. The bottom biplot records a different colour for each batch and this allows an assessment of the variation for cartridges from the same batch. However, the large number of observations leads to a large number of different colours, some of which are not able to be discerned.

The red arrows shown in the top biplot represent the "projected axes" for each variable, which are labelled accordingly (NB: the R program has placed an "x" before the variable name). The projected axes show how the original variables have been projected into the two-dimensional reduced space of the biplot [36]. The projected axes can be used to determine the relative effect each variable is having on the analysis. The direction of the arrow shows which direction the variable is causing the observations to be relatively placed. The length of the arrow shows the relative influence of each variable on the data, with the longer arrows representing variables which are having a larger influence on the placement of the observations within the biplot. The projected axes can also be used to assess the correlation between different variables. The correlation can be assessed by observing the spacing between the arrows, where the cosine angle between the arrows is approximately equal to the correlation between the variables [34]. Two variables with arrows that nearly overlap are highly correlated (e.g. 4x and 10x are highly correlated. The high correlation results from these two data points lying on the same vertical axis). High correlation between variables indicates that the variables show similar patterns within the data. When highly correlated variables are used in an analysis the variables are essentially providing the same information, therefore in most cases one of the variables can be removed, or conversely they can be combined.

6.1 PRELIMINARY ANALYSIS OF ORIGINAL COORDINATE DATA

The data from each sampled headstamp in this project was originally collected in the form of 22 Cartesian coordinates. These coordinates were subsequently standardised in order to provide consistency in the data collected from each headstamp (see 4.9.1). At this point in the analysis the data consisted of 715 different observations, with each observation consisting of 22 different Cartesian coordinates. The analysis methods available were unable to treat the x and y values from each Cartesian coordinate as a unified variable, therefore each x and y value was treated separately. This meant the analysis was composed of 44 different variables for each observation.

6.1.1 Dimension Reduction by PCA

From analysis of the PCA summary it was determined that a biplot of the first two principal components would give a fair representation of the data set, as together these components described approximately 73% of the variance in the data.

The PCA biplot (Figure 6.1) shows four main groupings of the data with a considerable spread of the observations between the four groups. The majority of the x coordinates from each data point appear to be highly correlated in the reduced space defined by the principal components as shown by the spacing of the projected axes. Similarly, the majority of the y coordinates also show high correlation.

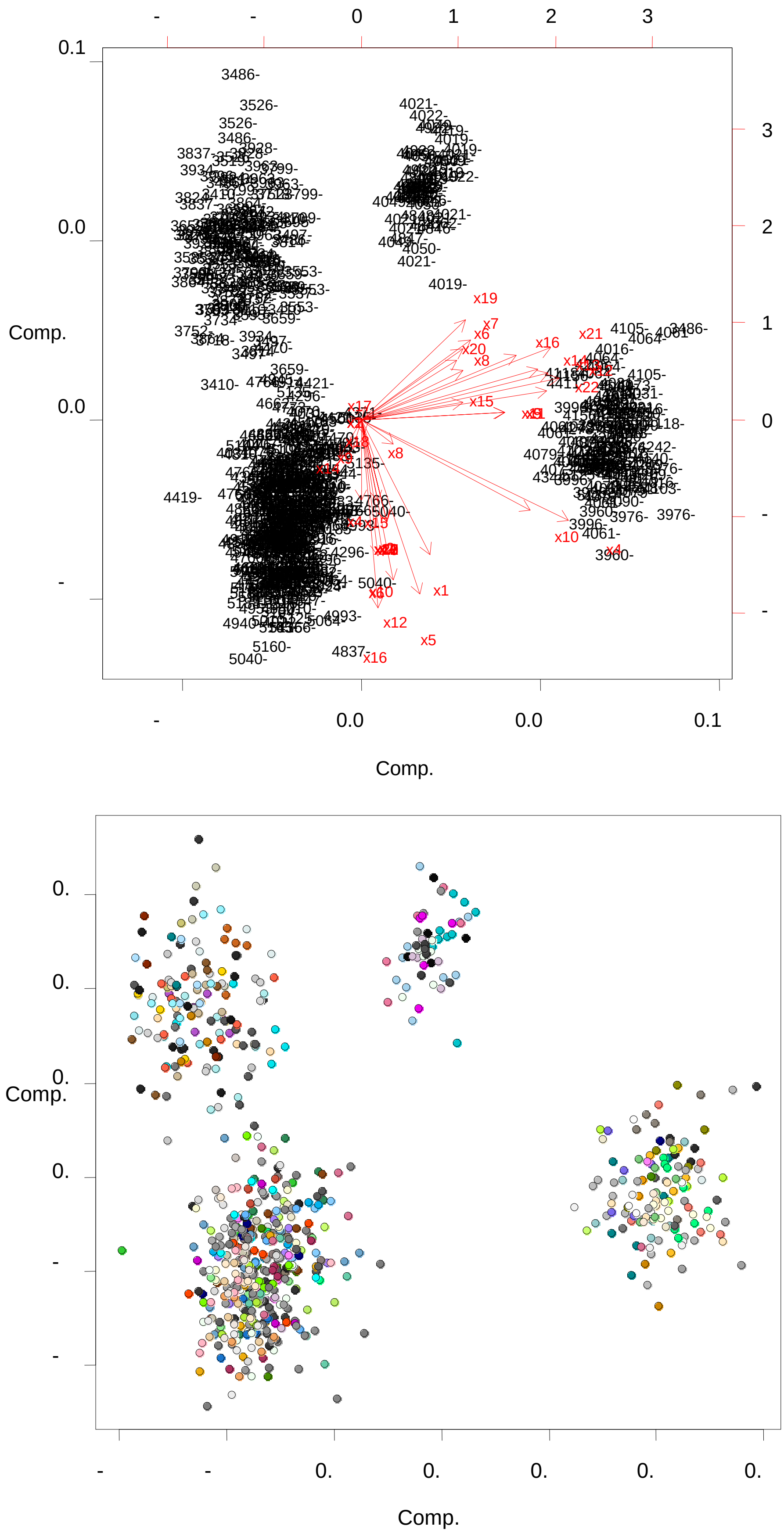


Figure 6.1: Principal components biplots for all of the coordinate data from all of the sampled cartridges. Top: The data has been labelled with batch number and sample number. Bottom: The data has been labelled by designating a different colour to each batch number.

6.1.2 Problems with using Original Coordinate Data

The main problem associated with using the standardised Cartesian coordinates was that each x and y coordinate was being considered separately. This created a large number of variables (44) which were used in the analysis. The computing power available was sufficient for dealing with large numbers of variables, however assessing which variables were having the largest influence on the analysis was difficult. Similarly, assessing which variables were causing scattering of the data was difficult. Treating each x and y value separately could have been suppressing further information which could be gained from the coordinate data.

From the analysis of the projected axes it was apparent that there were substantial correlations between most of the x coordinates and most of the y coordinates. This caused the two major factors (the correlated x coordinates and the correlated y coordinates) causing the groupings of the data to be working essentially in two directions. This could have been inhibiting the clustering of different groups and sub-groups within the data. Although the use of the data in its raw coordinate form was useful in the exploration of the data, it was decided that transforming the data would yield more information. This could help identify further variation between the headstamps in order to provide improved grouping of the data.

6.2 ANALYSIS USING DATA TRANSFORMATIONS

The calculation of data transformations is detailed in 4.9.3.

The use of data transformations served to substantially reduce the number of variables used for statistical analysis in this project. The reduction in variable number was the direct result of combining two (or more) coordinates into a distinct measurement. For example, when considering the data transformation referred to as *Left "I" height*, this data transformation involved combining the coordinates from two data points (one from the top of the "Left I" and one from the bottom of the "Left I"), each of which had an x and y coordinate. The use of data transformations reduced the number of variables in the statistical analysis from 44 to 17. This dramatically simplified the statistical analysis. The 17 data transformations used in this analysis can be found in Table 4.1 (see 4.9.3).

Advantages of using data transformations included:

- Simplified interpretation of the variables. Each of the data transformations represented a physical measurement of the various parameters of the headstamps. This also assisted understanding why some variables were having a larger influence on the data than others.
- Strengthening of the variables. Combining coordinates into a single variable helped expose relationships between the data points which were not necessarily identified when the coordinates alone were used [36].
- Removal of irrelevant data. With the collected coordinates there were multiple data points which were collected along the same vertical or horizontal plane. For instance, data points 1, 2 and 3 (see 4.8.2) all resided on the same vertical plane and therefore the x value for each of these coordinates was the same (except for some small experimental error). The use of data transformations eliminated repeating variables.

6.2.1 Dimension Reduction by PCA

PCA was performed on all of the data transformations in order to visualise the underlying relationships within the data. A biplot of principal component 1 versus principal component 2 (Figure 6.2) was deemed to give a fair representation of the data set, as these two components described approximately 74% of the variance in the data.

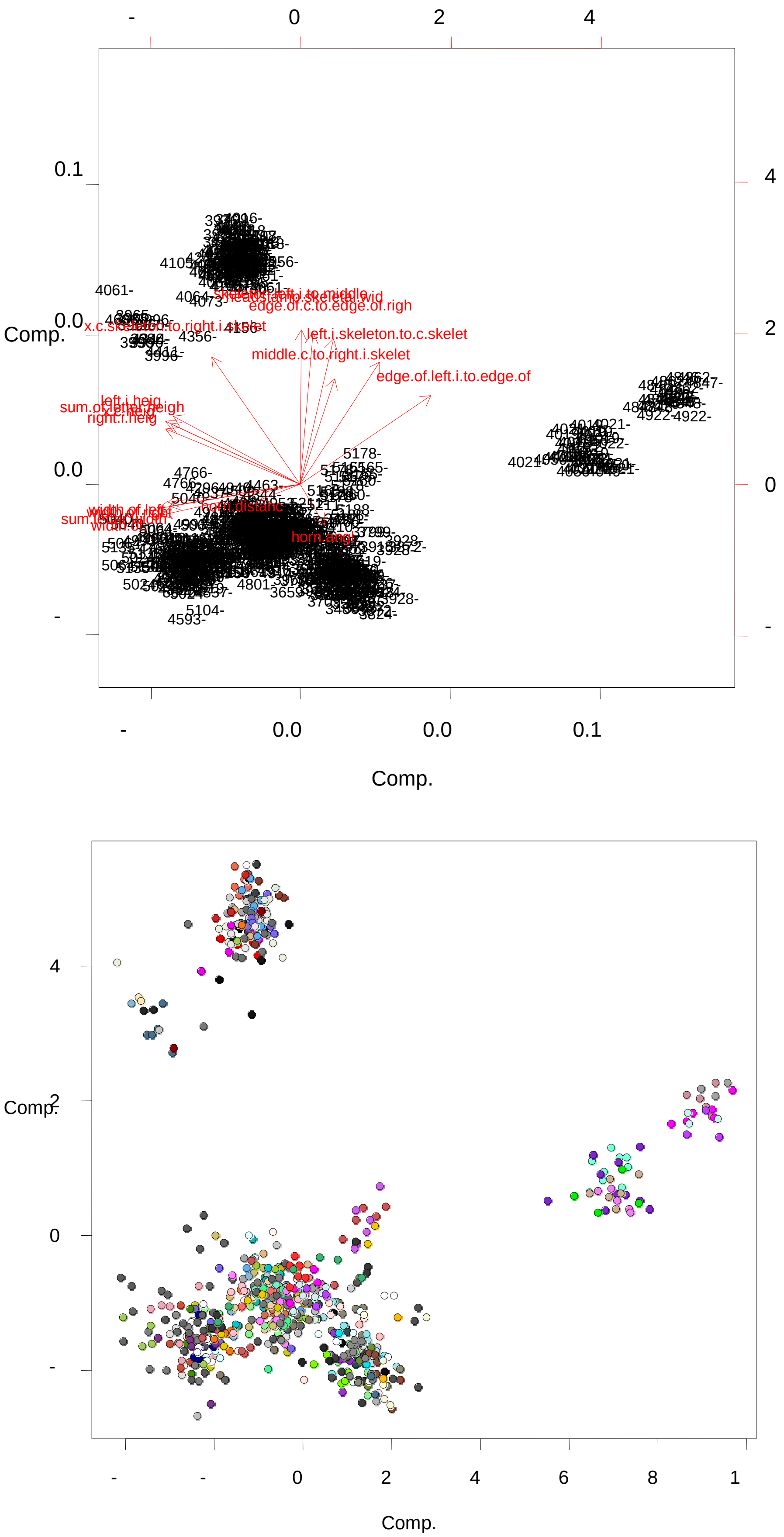


Figure 6.2: Principal component biplots for all of the data transformation from all of the sampled cartridges. Top: The data has been labelled with batch number and sample number. Bottom: The data has been labelled by designating a different colour to each batch number.

6.2.2 Problems with using all Data Transformations

The PCA biplot for all the data transformations (Figure 6.2) appeared to show more detail within the data than previously seen when the original coordinates were used. Where there were four distinct groups in the original coordinate analysis, the analysis of the data transformations showed greater separation. The majority of the data was encased within the larger grouping (bottom left) which is perhaps separated into three overlapping clusters. There was also the appearance of three other smaller groups in the biplot. In general, each grouping in the biplot was relatively tightly packed indicating less scattering of the data. Analysis of the projected axes showed extensive correlation between multiple variables in the reduced space defined by the principal components. For instance, the projected axes corresponding to *Left "I" height*, *"C" height*, *Right "I" height* and *Sum of letter heights* (found at approximately 10 o'clock) show a close relationship as indicated by the closeness of the spacing of the arrows. The correlation between these variables is not surprising as although the heights of the lettering between different headstamps may differ, one would expect the heights of the lettering within a headstamp to be relatively constant.

The PCA using the data transformations showed considerable promise, however ideally the groupings would be separated further.

The substantial correlations seen between some of the variables indicates that some variables can be removed from the analysis without losing information about the data. This may also help separate the groupings, with particular regard to the three groupings which are close together.

All the data transformations were being used in this analysis, therefore it was likely that some of these transformations were having a much larger effect on effectively grouping the data whereas other transformations could have been having little effect or even impacting negatively on the grouping of the data. Consequently, it was important to perform some analysis in order to determine the relative influence of each data transformation. Such an analysis would likely lead to further reduction of the number of variables so that only the variables which were leading to effective discrimination of different headstamp types were being used.

6.3 EXPLORING THE IMPORTANCE OF EACH DATA TRANSFORMATION

To assess which transformations were most meaningful, a study was conducted on the variability of the data transformations within the headstamps that were produced over time. This study was performed to provide an effective means for selection of the most important variables to be used in the statistical analysis.

6.3.1 Variability of Headstamps with Time (Batch Number)

The value of each data transformation for each cartridge was plotted against batch number. These graphs were used to show how the measured parameters of the headstamps changed over time. These were useful in order to see if there were patterns of change within each data transformation or if the variation was random. Assessing the influence of each data transformation would allow the identification of the discriminating data transformations and removal of non-discriminating data transformations.

The resulting graphs for each data transformation can be found in Appendix II. Further graphs were also produced for some of the standardised coordinates (15x, 15y, 16x and 16y) and for the diameter of the heads of the cartridges across the vertical and horizontal planes (see 4.9.3).

6.3.2 Discussion

Instead of discussing each graph in turn, the general trends for some of the graphs will be explained with examples of the variables providing high-quality discrimination and those providing lower-quality discrimination between the headstamp variants that appear throughout production.

6.3.2.1 Left "I" Height

The graph for *Left "I" Height* versus Batch Number is shown in Figure 6.3. The trends shown in this graph were typical of the transformations relating to the letter heights. This explains the highly correlated nature of the variables that was seen in the PCA biplot (Figure 6.2). Various groupings in the graph have been labelled.

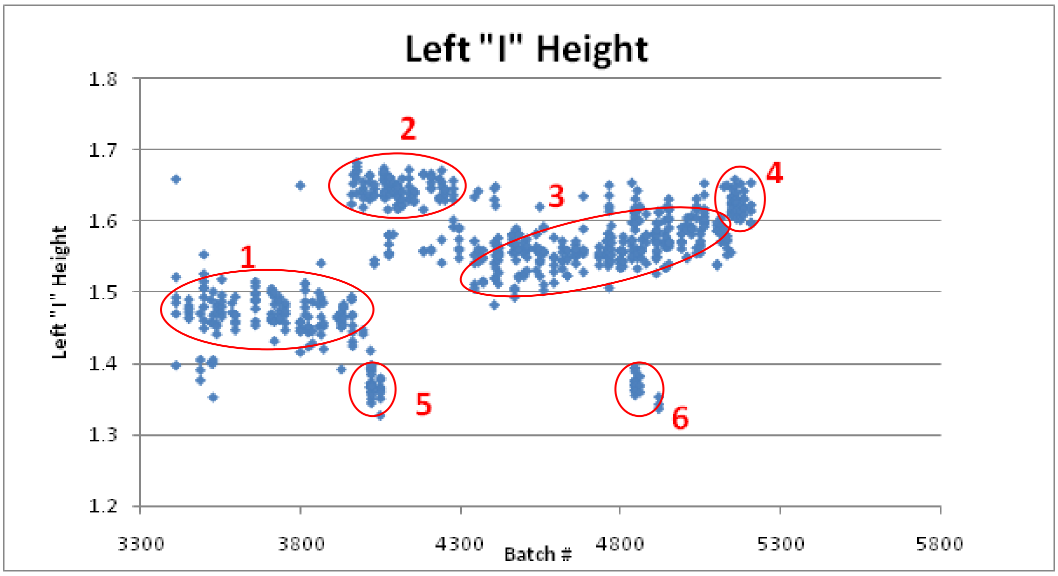


Figure 6.3: Graph showing the *Left "I" Height* vs batch number for all of the sampled cartridges.

Groups 1 and 2 loosely corresponded to Dr Sprott's Category 3 and Wide-I headstamps respectively. Groups 3 and 4 corresponded to Dr Sprott's Category 4 headstamp, and the remaining groups (5 and 6) were not identified in Dr Sprott's original analysis.

An interesting feature of this graph revolved around group 3. This group had an upward trend indicating a possible change in headstamp design where the letter heights were slightly increased. However, this variable alone seemed insufficient to sufficiently discriminate the design change if it had occurred.

Group 4 can be seen as having almost intermediate letter heights of the headstamps seen in groups 2 and 3. Group 4 was not initially categorized as a separate entity from group 3 (and/or group 2) however further analysis of this group showed that these cartridges were wet primed. This indicated a possible manufacturing source of difference between the wet-primed cartridges of Group 4 and the dry-primed cartridges of groups 2 and 3. Further analysis of the other variables showed that this group was able to be discerned from the other cartridges (see 6.3.2.2).

Groups 5 and 6 had essentially the same letter heights and further analysis of these groups showed the cartridges to have also been wet-primed. These groups were the Tenex headstamps (group 5) and the headstamps of English manufacture (group 6) (see 2.3.3). Further analysis of the other variables showed these two groups were able to be discerned, particularly with regard to letter widths (see 6.3.2.2).

6.3.2.2 Width of Right "I"

The graph for the *Width of Right "I"* versus Batch Number is shown in Figure 6.4. The trends shown in this graph were fairly typical for graphs produced outlining the width of the letters. Where appropriate the same group labelling system as used in Figure 6.3 has been applied. New sub-groups have been given new labels.

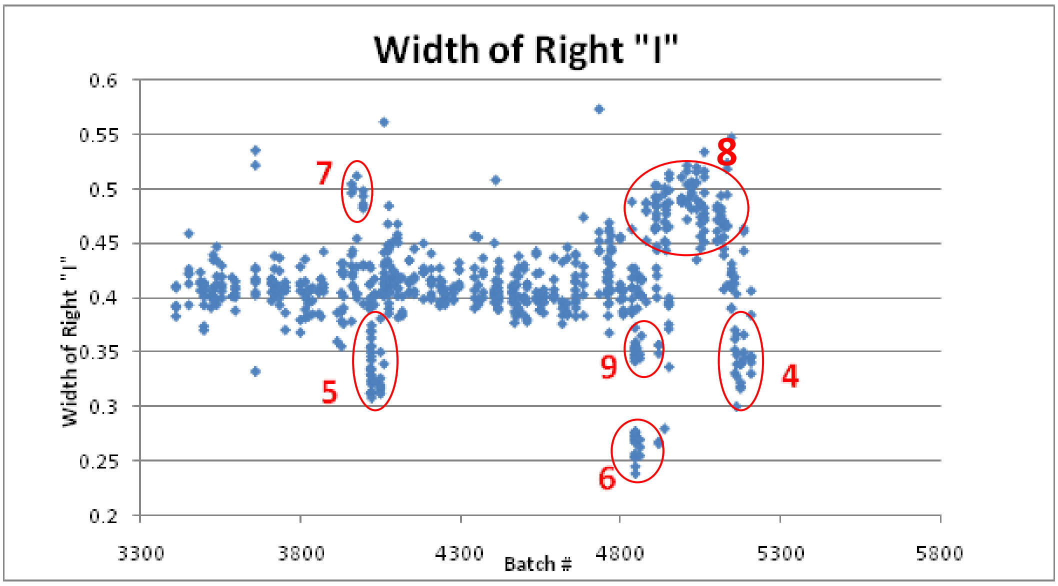


Figure 6.4: Graph showing the *Width of Right "I"* versus batch number for all of the sampled cartridges.

In this graph the groups labelled 1, 2 and 3, which were able to be discerned by letter height (Figure 6.3), were no longer able to be discerned. All three of these groups lay within the main cluster of the data, with a *Width of Right "I"* of around 0.4mm. Interestingly, group 8 (a sub-group of group 3) was able to be separated from the rest of group 3 as this subgroup had a slightly thicker right "I". This confirms that a slight change in headstamp design occurred as suggested by the upward trend of group 3 seen in Figure 6.3.

Figure 6.4 also shows that group 4 (wet primed) was distinct from groups 2 and 3 (dry primed) as the headstamps in this cluster had significantly thinner letters.

The graph also shows that some difference exists between the wet-primed cartridges which make up groups 5 (Tenex) and 6 (English Manufacture). This was expected as the headstamps of English manufacture have significantly thinner lettering than that seen in the Tenex headstamps (Figure 2.7).

A further sub-group of group 3 also appeared which has been labelled group 9. Further analysis of the cartridges within this group showed that these were derived from the boxes of “Imperial” brand ammunition with these cartridges being wet-primed. Taken together, this shows the wet-primed cartridges of groups 4, 5, 6 and 9 have significantly thinner letters than what is seen in the dry-primed cartridges. Consequently, the wet-primed cartridges can be separated from the dry-primed cartridges on letter width alone. However, discriminating between the various batches of wet-primed cartridges (e.g. discriminating between groups 4 and 5) was not possible with this variable.

6.3.2.3 Horn Distance and Horn Angle

A variable providing lower-quality discrimination is illustrated by *Horn Angle*. This has been contrasted to the information gained from the *Horn Distance* measurement.

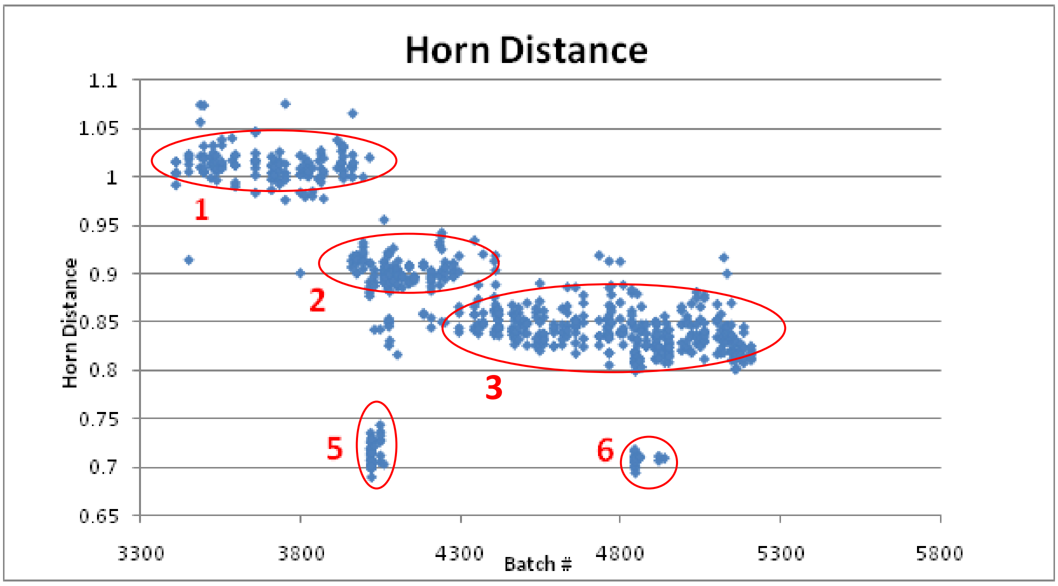


Figure 6.5: Graph showing the *Horn Distance* versus batch number for all of the sampled cartridges.

Horn Angle and *Horn Distance* are two related variables as these both assess and make some attempt to measure the features of the horns of the “C” in the headstamps. The graph of *Horn Distance* (Figure 6.5) shows patterns in the data which are not too dissimilar from what was seen in the graph of *Left “I” Height* (Figure 6.3). The majority of the data falls into three distinct groups labelled groups 1, 2 and 3 which loosely relate to Dr Sprott’s Categories of headstamp (3, Wide-I and 4 respectively). Two different clusters of wet-primed cartridges (groups 5 and 6) can also be seen which have a significantly smaller horn distance than seen in the other groups.

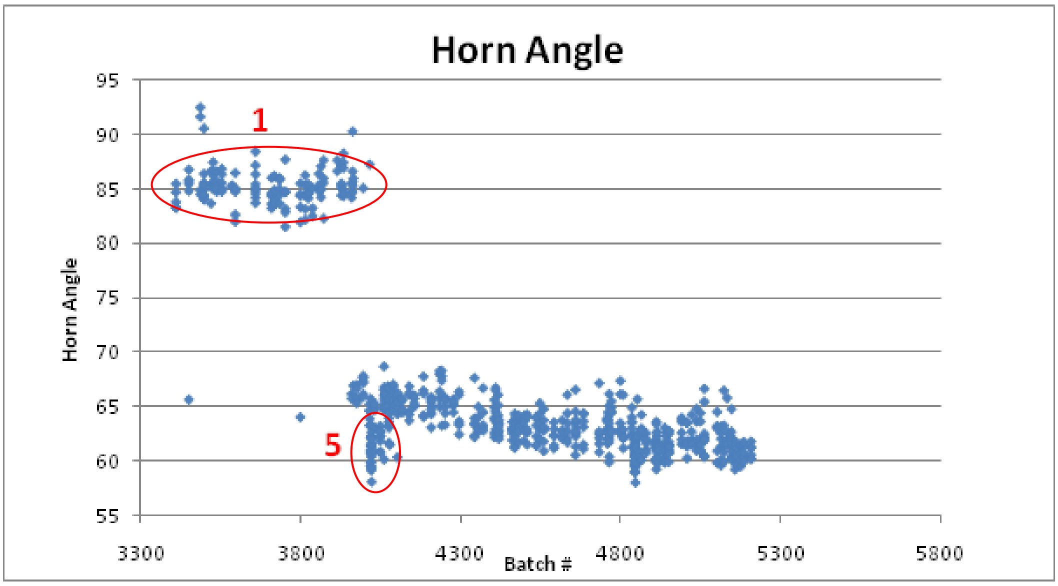


Figure 6.6: Graph showing *Horn Angle* versus batch number for all of the sampled cartridges.

It is apparent that significantly less information can be gained from using *Horn Angle* as a variable (Figure 6.6). Group 1 (Dr Sprott's Category 3) can be identified as having a substantially larger *Horn Angle* than the rest of the data. A small cluster corresponding to the wet-primed cartridges of group 5 can also be partially identified. The remaining data does not effectively differentiate into different groups because there are only minute differences present in the horn angles of the different variants of headstamp. For this reason, using *Horn Distance* as a variable in the statistical analysis provides much more information for grouping the data compared to that gained from using the *Horn Angle*. This was an interesting finding given the emphasis surrounding the use of *Horn Angle* in the original analyses performed on the sans-serif-ICI headstamp during the 1980 Royal Commission of Inquiry (see 1.1.4). This finding demonstrated that *Horn Distance* (a variable used by Mr McDonald) may have been more useful for discriminating between the different headstamp variants.

6.3.2.4 Coordinates 16x and 16y

Two variables providing no information for discrimination of the relative variants of headstamp are shown in Figures 6.7 and 6.8. These variables are the standardised coordinates (x and y) which relate to the middle of the head of the cartridge relative to the headstamp (NB: these coordinates contain the information regarding the position of the headstamp within the head of the cartridge).

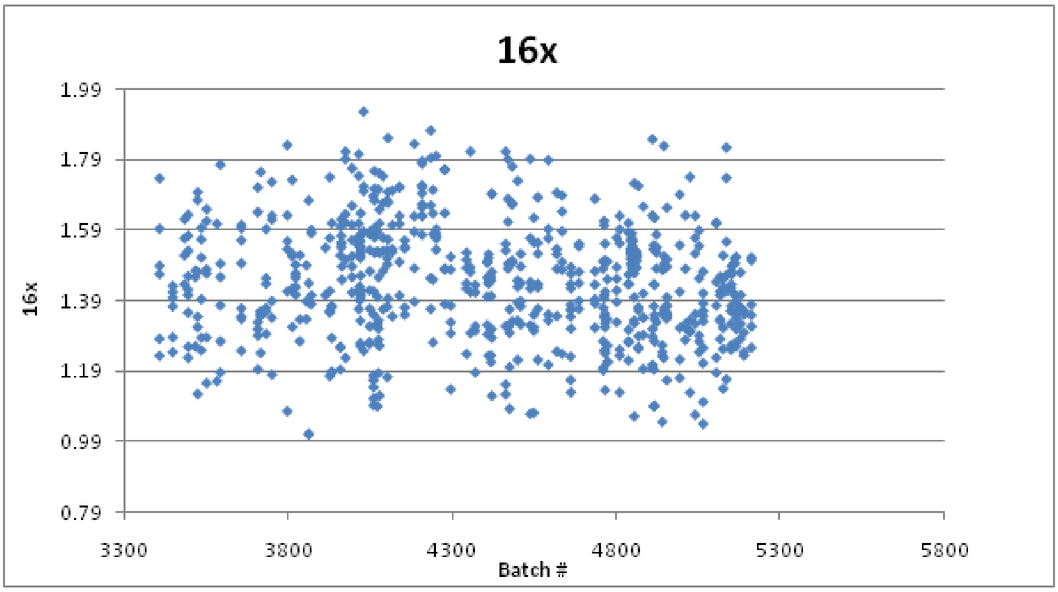


Figure 6.7: Graph showing the value for 16x (standardised coordinate) versus batch number for all of the cartridges.

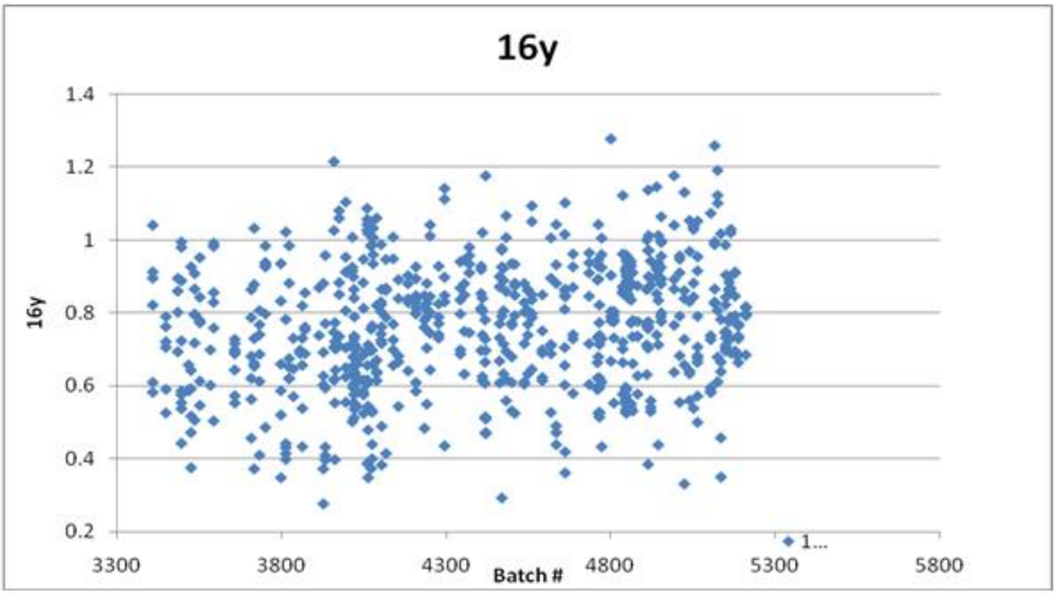


Figure 6.8: Graph showing the value for 16y (standardised coordinate) versus batch number for all of the cartridges.

Figures 6.7 and 6.8 show that the data is scattered with no discernable pattern. This shows that these variables offer no useful information for discerning the different variants of headstamp. Including these variables in the statistical analysis would cause random scattering of the data which was not useful for this project.

6.3.3 Summary

Each of the transformations were graphed against batch number and assessed. The appropriate groups were identified within each graph and the observed results were linked back to what could be seen in the headstamps. This helped identify which variables were providing discrimination of the appropriate groups.

This analysis also assisted in identifying various outliers within the data which could be checked and related back to the appropriate sampled headstamps. The main reasons causing the formation of outliers were:

- Severely damaged headstamps as the result of bunter wear.
- Cartridges of probable impure provenance.
- Genuine headstamp variants.

Where the outliers were formed by severely damaged bunters and the data was deemed to be useless, the data was removed. Cartridges of probable impure provenance were not removed from the data due to uncertainty and the possibility of these being genuine. Genuine headstamp variants that were identified were noted. An example of a genuine headstamp variant was identified in group 7 (Figure 6.4).

Each variable appeared to have strengths and weaknesses when it came to discriminating between the variants of the headstamps. For instance, *Left "I" Height* (Figure 6.3) was good for discriminating groups 1, 2, 3, 5, 6 and partially group 4, however this did not identify the sub-groups of group 3 (groups 8 and 9). In contrast, *Right "I" Width* (Figure 6.4) did not discriminate between groups 1, 2 and 3 but this did identify two sub-groups of group 3 (groups 8 and 9). This variable also separated group 4 from group 3 and provided a discriminating factor between groups 5 and 6.

Various combinations of the important variables were analysed using PCA. A typical example of one set of variables trialled is shown in Figure 6.9.

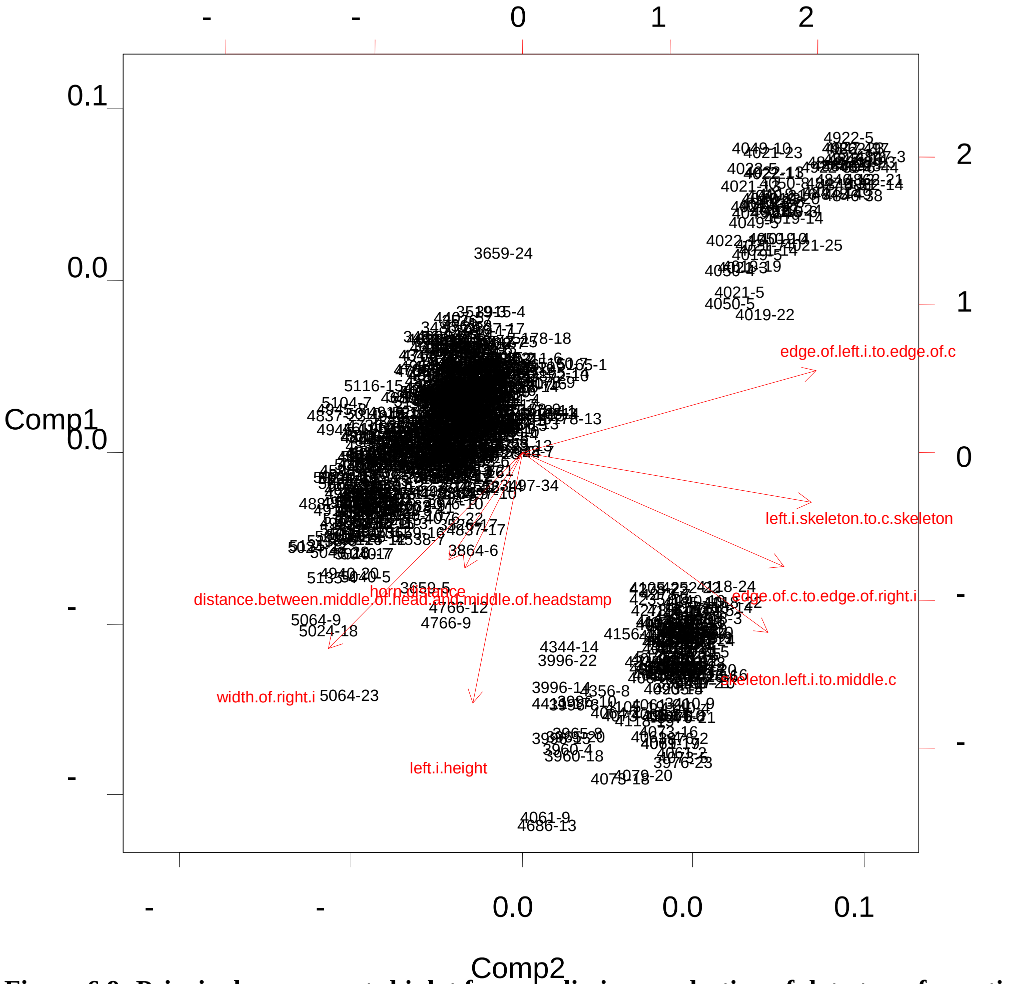


Figure 6.9: Principal components biplot for a preliminary selection of data transformations from all of the sampled cartridges.

From observation of the PCA biplots it was clear that the analyses were yielding insufficient separation of the relative headstamp variants even though the variables which were having the largest influence on the headstamps had been selectively used in the analyses. The following points summarise where the problems arose:

- Some variables provided good separation between the headstamps from wet-primed cartridges and those from the dry-primed cartridges (e.g. *Width of Right “I”*).
- These same variables provided little discrimination of the variant headstamps that existed within the dry-primed cartridges and those that existed within the wet-primed cartridges.
- Therefore, when these variables were used the wet-primed cartridges were sufficiently discerned from the dry-primed cartridges however there was little separation of the variant headstamps within the dry-primed cartridges and similarly within the wet-primed cartridges.

- The variables that were useful for discriminating between the variant headstamps within the dry-primed and wet-primed cartridges were being somewhat masked by the effects of the variables which were separating the dry-primed cartridges from the wet-primed cartridges.

A partial solution to this problem involved dividing the data into two distinct groups of wet-primed and dry-primed cartridges. By dividing the data into wet-primed and dry-primed cartridges, a specialised selection of variables could be used for each analysis. The end result of such analyses would allow discrimination of all of the variant dry-primed headstamps in a single analysis and all of the variant wet-primed headstamps in a separate analysis.

6.4 CATEGORISING THE DATA INTO WET-PRIMED AND DRY-PRIMED CARTRIDGES

Dividing the data into separate groups for wet-primed and dry-primed cartridges was trivial as the primed state of each sampled cartridge had been determined and recorded during sampling.

Implementing a separate scheme of classification according to the primed state of a cartridge was not seen as problematic when considering the application of this method for predicting the time of manufacture of unknown cartridges. Although the distinction between wet-primed and dry-primed cartridges relates to a design difference inside the cartridge case (the state of the priming mix during priming), the method of manufacture creates a difference in the rim which allows differentiation for unfired and fired cartridge cases (see 2.3.4). This means the primed state of an unknown cartridge (e.g. one found at a crime scene) can be determined, which could be followed by analysing the headstamp on the cartridge in the appropriate analysis (dry primed or wet primed)

Following categorization of the data into wet primed and dry primed, the relevant data transformations were reassessed to determine which were able to provide effective discrimination between the variants of headstamp. This was performed using the same method as documented in 6.3.

6.4.1 Dry-Primed Cartridges – Selection of Important Variables

The individual graphs for each data transformation versus batch number for the dry-primed cartridges are contained within Appendix III.

The headstamps from the dry-primed cartridges could be broadly split into three different variants of headstamp with regard to the majority of the data transformations. These groups are shown in the graph of *Horn Distance* versus batch number (Figure 6.10). The groups have been labelled 1, 2 and 3. Group 1 represents Dr Sprott's Category 3 headstamps, group 2 represents Dr Sprott's Wide-I headstamp and group 3 represents Dr Sprott's Category 4 headstamps. There appeared to be significant differences between the groups indicating that true differences do exist between the headstamps. This suggests that these three groupings should be easily discerned by PCA.

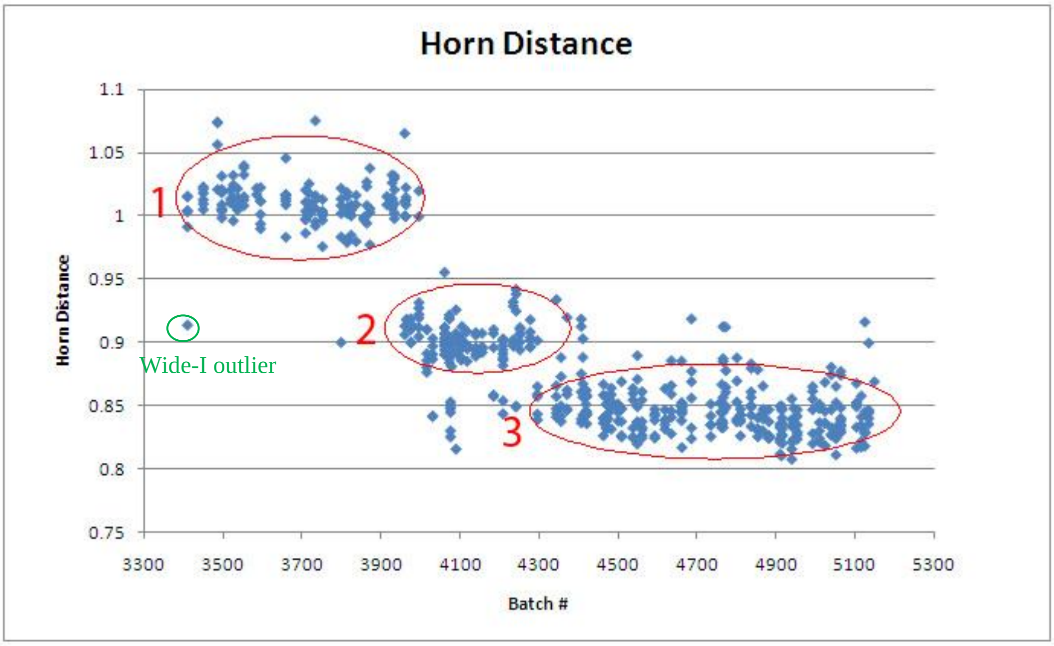
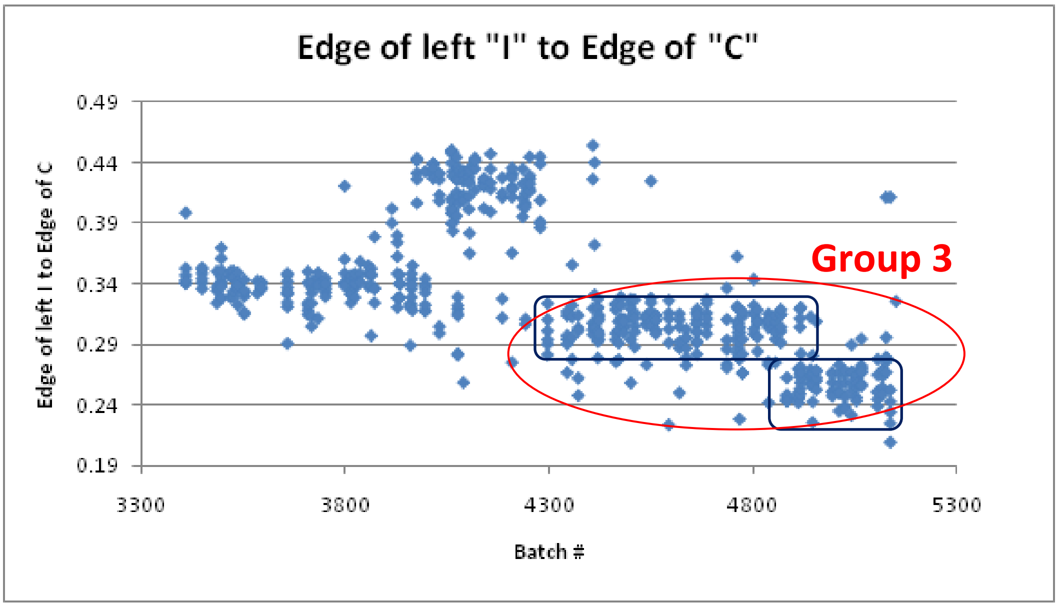


Figure 6.10: Graph showing *Horn Distance* versus batch number for the dry-primed cartridges.

Interestingly, a sub-group of group 3 was able to be discerned from the other dry-primed cartridges for some of the variables, namely *Width of Right "I"* and *Edge of Left "I" to Edge of "C"* (Figure 6.11). This group was the same group that had been identified previously in Figure 6.4 where it was labelled group 8. This group was a sub-group of the Category 4 headstamps. Accordingly, the main group of the Category 4 headstamps have been renamed Category 4a with the new sub-grouping being labelled Category 4b. Photographs of the Category 4a and 4b headstamps are shown in Figure 6.12. The variables capable of distinguishing the Category 4a and 4b headstamps were important for the statistical analysis to ensure that these variant-Category 4 headstamps were sufficiently discerned.



6.11: Graph showing *Edge of Left "I" to Edge of "C"* versus batch number for the dry-primed cartridges. Group 3 has been outlined (red) with the sub-groupings of group 3 identified (black).

Figure 6.12: Photographs showing the closely related Category 4a and 4b headstamps. Left: A Category 4a headstamp. Right: A Category 4b headstamp.

Some of the outliers seen in the graphs appeared to be consistently lying outside the main data groups. This could indicate some minor variants of the headstamps. Additionally, some of the outliers appeared to have been caused by cartridges of probably impure provenance (see 11.1). An example of such a headstamp can be found in batch 3410. One of the headstamps sampled in this batch was of the Wide-I category. The data point relating to this Wide-I headstamp was easily observed as an outlier in the majority of the graphs (Figure 6.10 - "Wide-I outlier"). This data point was not removed, as it may have been genuine, indicating a mix of headstamps within this batch. However, the appearance of Wide-I headstamps this early in production was unlikely which suggest this cartridge was probably introduced into this box from a box of later manufacture.

Some of the variables had a large scattering effect on the data. Scattering of the data could have been caused by small changes in various dimensions of similar headstamps (probably from bunter wear) or this could have been caused by experimental error during data collection. The variables which were causing large scattering of the data were avoided when selecting the variables to be used in the statistical analysis.

The information obtained from the graphs of the various data transformations were used to select a number of variables for the subsequent statistical analysis.

6.4.2 Wet-Primed Cartridges – Selection of Important Variables

The individual graphs for each variable versus batch number for the wet-primed cartridges are contained within Appendix IV.

The general trend shown in the graphs indicated that the headstamps of the wet-primed cartridges could be broadly categorized into two main groups. A labelled graph for *Left "I" Height* versus batch number for the wet-primed cartridges is shown in Figure 6.13.

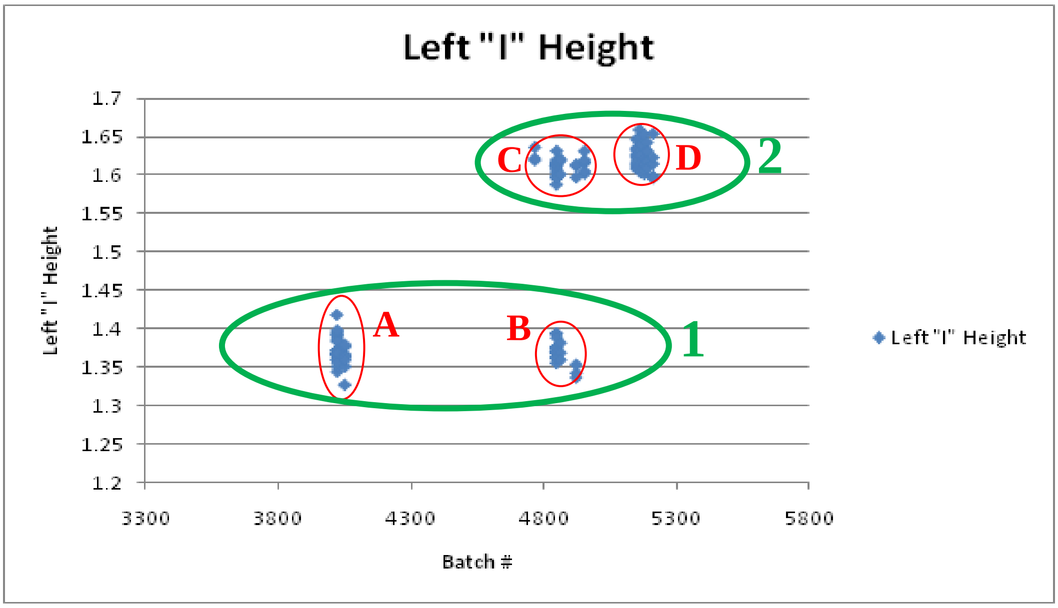


Figure 6.13: Graph showing the *Left "I" Height* versus batch number for the wet-primed cartridges. The two main grouping and have been labelled (green) as well as various clusters (red).

The first group (group 1) was composed of the clusters labelled A and B (Figure 6.13). Upon further examination of the data it was found that cluster A related to the Tenex headstamps (see 2.3.3). These were produced by CAC intermittently between batch numbers 3971 and 4055 [5]. Cluster B related to the headstamp that was produced at ICI Australia by bunters of English manufacture (see 2.3.3). It was not surprising that these two types of headstamps were grouped together with regard to the majority of the variables. Both headstamp types have characteristic square-ended lettering and the dimensions of the headstamps are very similar (Figure 2.7). However, there is a major difference in the widths of the letters. The Tenex headstamps have considerably wider lettering than that seen in the headstamps produced from bunters of English manufacture. The difference in letter width can be seen in Figure 6.14. For this reason the variables regarding letter width were important for the statistical analysis of the wet-primed cartridges to ensure that the Tenex headstamps and the headstamps produced by bunters of English manufacture were able to be discerned.

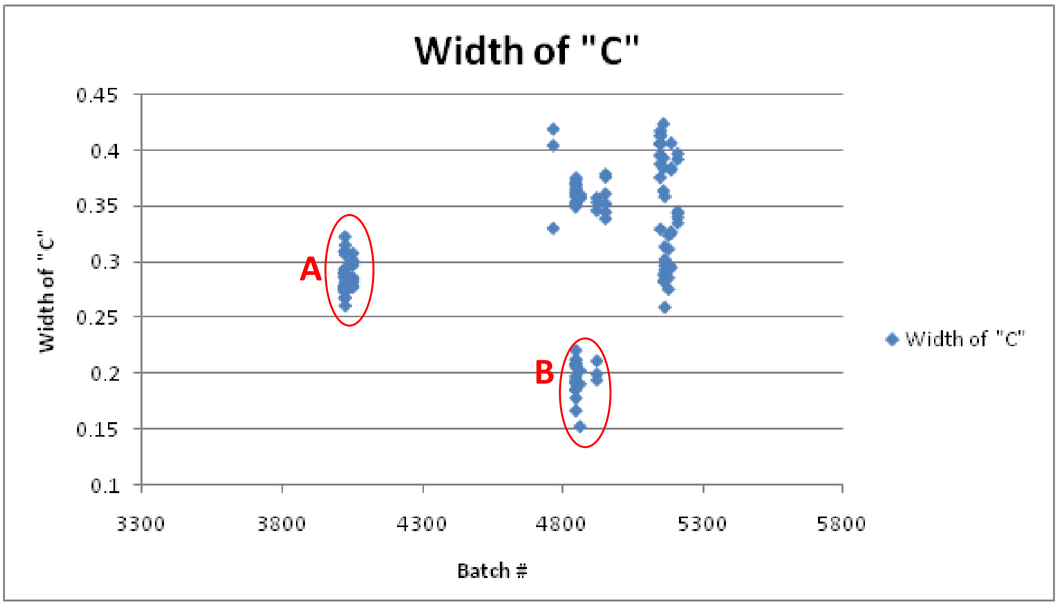


Figure 6.14: Graph showing the *Width of "C"* versus batch number for the wet-primed cartridges.

The cartridges bearing the headstamps of English manufacture (cluster B) were contained within "Imperial" brand ammunition. This particular brand of ammunition produced by CAC is known to contain genuine mixtures of cartridges bearing different headstamps. This was evident in the graphs as the headstamps from the Imperial branded ammunition (batches 4845-4849 and 4919-4927) were split between clusters B and C (Figure 6.13).

The other main group of headstamps from the wet-primed cartridges (group 2) was composed of clusters C and D (Figure 6.13). Cluster C contained headstamps from cartridges that have been derived from three different sources: cartridges from the Imperial brand ammunition (those which were not headstamped by the bunters of English manufacture); cartridges rejected from the "Mark10" brand of ammunition; and cartridges from a box of ammunition containing a mix of wet and dry-primed cartridges (batch 4766).

The Mark10 brand of ammunition was marked as an accuracy brand specifically designed for .22 match rifle shooting [3]. The Mark10 reject cartridges were those that were deemed to be inadequate for the Mark10 brand and hence these were loaded into "Standard Non-Rusting" branded ammunition.

The box of cartridges containing a mix of wet and dry-primed cartridges was from batch 4766. The CAC production records did not reference any information regarding a mix of primed states for cartridges from this batch and therefore the provenance of this box was questionable.

Cluster D (Figure 6.13) contains the cartridges that were mainly loaded into "Supersonic" brand ammunition and also some cartridges from "Standard Non-Rusting" brand boxes. The batch numbers contained within this cluster ranged from around 5149 (packed on 17th August 1970) to 5211 (packed on 6th April 1971). The CAC production records state that from around 17th August 1970 onwards the majority of the cartridges used were wet-primed which supports the observation seen in cluster D. This was interesting as it contradicted evidence given by Mr Cook (Manager of the Ammunitions Division of ICI Australia) at the 1980 Royal Commission of Inquiry. Mr Cook stated that up until 20th October 1974 the majority of the cartridges produced by ICI Australia were dry-primed with only a small proportion produced by the wet-priming method (see 2.3.3). It would appear that Mr Cook may have been mistaken as large numbers of wet-primed cartridges appear to have been used much earlier than he stated.

The headstamps on the cartridges contained within clusters C and D appear to be very similar. Interestingly, these headstamps also appear be to be similar to Dr Sprott's Category 4 which was seen on the dry-primed cartridges. However, it is important to make the distinction that these headstamps are not identical to the Category 4 headstamps. Due to the similarities between these headstamps and Dr Sprott's Category 4 headstamps, they have been labelled Category 4c. The similarities between a Category 4 (dry-primed) headstamp and a Category 4c headstamp (wet-primed) can be seen in Figure 6.15.

Figure 6.15: Photographs comparing the similarities of Dr Sprott's Category 4 (dry-primed) headstamp and a Category 4c (wet-primed) headstamp. Left: An example of Dr Sprott's Category 4 headstamp. Right: An example of a Category 4c headstamp.

There does not appear to be a single variable capable of sufficiently separating clusters C and D (Figure 6.13) into distinct groups. This reflects the closely related nature of the Category 4c headstamps. However, some of the variables appeared capable of detecting some small differences between the headstamps which suggests some variants of the Category 4c headstamp exist. The graph showing the *Sum of the Letter Widths* versus Batch Number is shown in Figure 6.16.

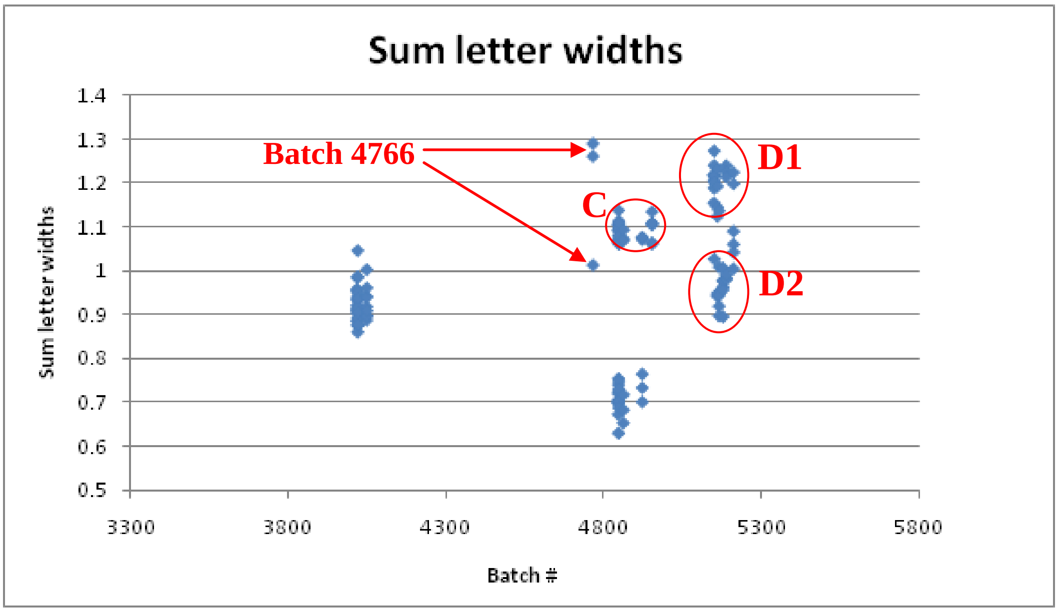


Figure 6.16: Graph showing the *Sum of Letter Widths* versus batch number for the wet-primed cartridges.

This graph shows that the Category 4c headstamps can be broadly split into three overlapping clusters (Clusters C, D1 and D2) which supports the suggestion that three variants of the Category 4c headstamps exist. From visual analysis of the headstamps there appears to be a slight difference in the letter widths of the Category 4c variants. The headstamps contained in cluster D1 have the thickest lettering; those contained within cluster C have intermediate widths of the lettering; and those contained in D2 have the thinnest lettering. However, the difference between the so-called Category 4c variants was very slight and it was unknown whether this was a true difference or if it had arisen through experimental error.

In Figure 6.16 the data points from batch 4766 have also been labelled. The provenance of this box of ammunition has already been questioned due to the presence of wet and dry-primed cartridges in the box. This graph shows that the headstamps from this box do not appear to lie within the grouping of the headstamps of the time (cluster C) and instead these appear to be mix of headstamps from cluster D1 and D2. This further supports the theory that this box of ammunition contained cartridges of impure provenance.

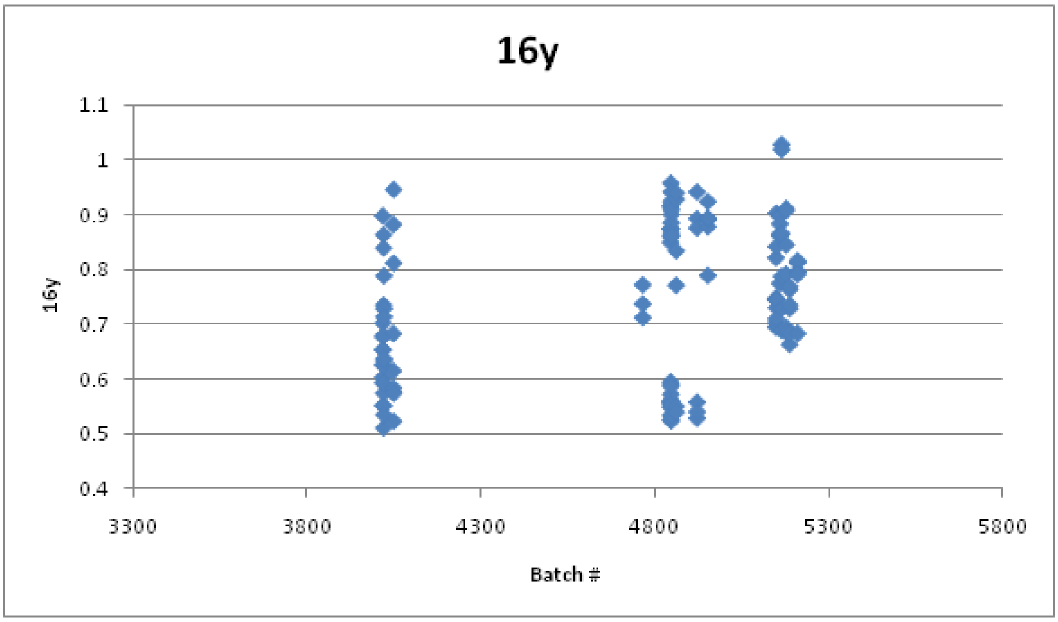


Figure 6.17: Graph showing the value for 16y (standardised coordinate) versus batch number for the wet-primed cartridges.

There appeared to be some correlation between the headstamps on the wet-primed cartridges with regard to where the headstamp was placed within the head of the cartridge as shown with the variables labelled 16x and 16y (Figure 6.17). The Tenex headstamps appear to be randomly scattered with regard to the headstamp placement on the cartridge, however the remaining headstamps appear to fall into three groups with some overlap between the groups. This was interesting as when these coordinates were graphed against batch number for all data, there appeared to be no correlation between the headstamps from different batch numbers (see 6.3.2.4). The same was observed when these variables were graphed against batch number for just the dry-primed cartridges (Appendix III). This shows that the placement of the headstamps on the heads of the dry-primed cartridges was essentially random, however there appears to be some information regarding where the headstamps were positioned on the heads of wet-primed cartridges.

The information obtained from the graphs of the various data transformations was used to select a number of variables for the subsequent statistical analysis.

7 – STATISTICAL ANALYSIS

The wet-primed and dry-primed cartridges were treated separately for the statistical analysis. During any statistical analysis no single statistical technique will answer all of the questions, therefore it was important to explore different approaches. The statistical techniques used to analyse the data included PCA, Hierarchical Clustering Analysis and LDA.

7.1 DRY-PRIMED CARTRIDGES

Exploration of the data collected from the dry-primed cartridges showed that the headstamps could be divided into four main categories that occurred sequentially during production. These categories loosely related to those previously defined by Dr Sprott in his analysis, therefore the same naming system was used. An extra category of headstamp was also able to be defined which was a variant of the Category 4 headstamp. Therefore the Category 4 headstamps were renamed Categories 4a and 4b.

From analysis of the cartridges sampled in this project the following observations were made: Category 3 headstamps were mainly seen between batches 3410 and 3963; Wide-I headstamps between 3965 and 4278; Category 4a headstamps between 4296 and 4867; and Category 4b headstamps between 4882 and 5135.

The data transformations which appeared to be having the largest influence on the headstamps from the dry-primed cartridges were identified in the biplots discussed in 6.4.1.

Various combinations of the data transformations were trialled in the statistical analysis of the headstamps. The results from the different combinations of data transformations were subjectively assessed according to the separation attained between the various groups. Additionally, the results from LDA were further assessed objectively by which combination of variables had the lowest error of predictions from cross-validation of the data.

During this process some additional variables were produced by combining tightly correlated data transformations. For example, *Left "I" Height* and *"C" Height* were combined to produce a combined variable. Combining closely associated data transformations leads to an increased influence of these variables on the data, however care must be taken to ensure that valuable information was not lost.

From the analyses performed the following variables appeared to be offering the greatest discrimination between the batches of cartridges:

- *Horn Distance.*
- *Width of Right "I".*
- *Width of "C".*
- *Sum of Left "I" and C" Heights.*
- *Right "I" height.*
- *Edge of Left "I" to Edge of "C".*
- *Edge of "C" to Edge of Right "I".*
- *Left "I" Skeleton to "C" Skeleton.*
- *"C" skeleton to Right "I" Skeleton.*

Accordingly, these variables were used in the statistical analysis for the dry-primed cartridges.

7.1.1 Dimension Reduction by PCA

From analysis of the PCA summary it was determined that a biplot of the first two principal components (Figure 7.1) would give a fair representation of the data set, as these together described approximately 79% of the variance in the data set.

The PCA biplot (Figure 7.1) showed that there were three major groupings within the data which have been labelled Group 1, 2 and 3.

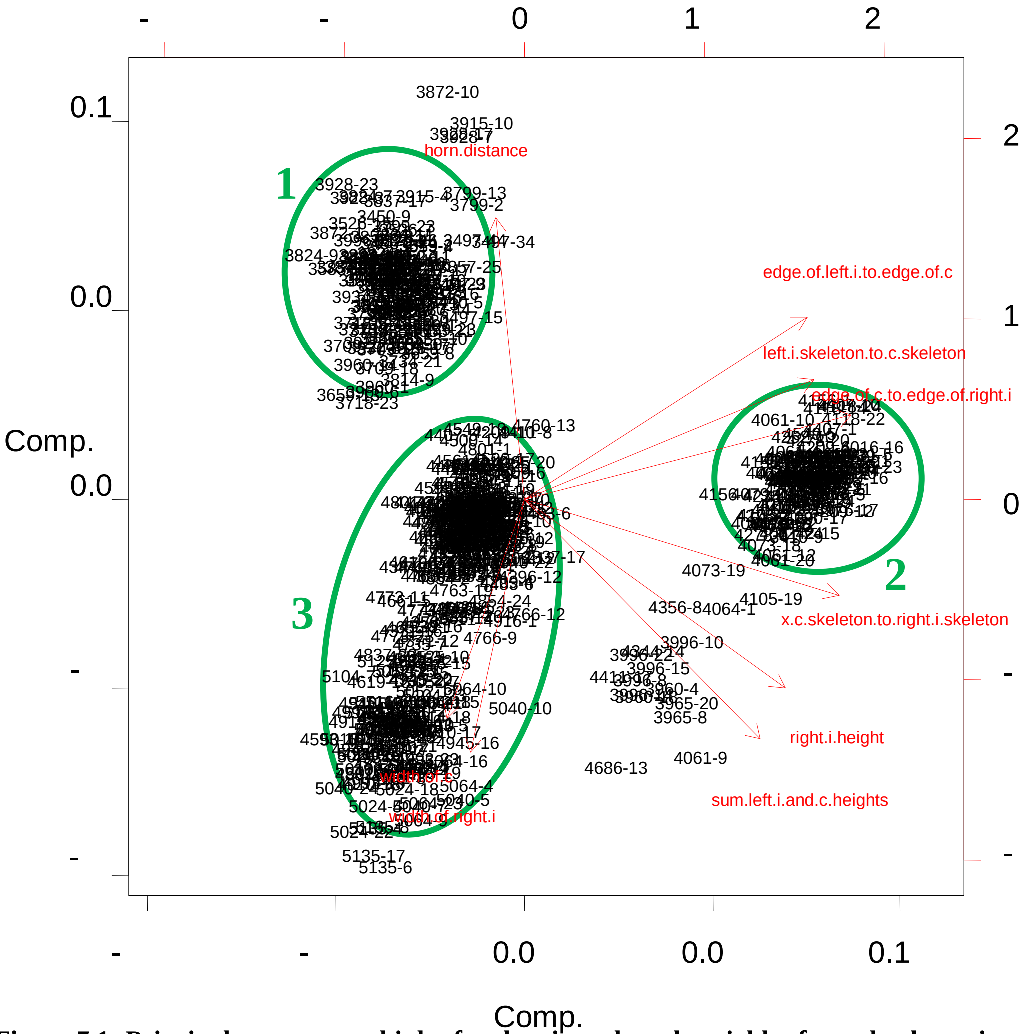


Figure 7.1: Principal components biplot for the nine selected variables from the dry-primed cartridges.

7.1.1.1 Group 1 (Category 3)

The headstamps from the cartridges contained within group 1 broadly correlated to Dr Sprott's Category 3 headstamps. The batch numbers contained within this group appear to be consistent with what is known regarding the period of production of Category 3 headstamps. This group appears to be relatively tightly packed with some small outliers.

7.1.1.2 Group 2 (Wide-I)

The headstamps contained within group 2 were of Dr Sprott's Wide-I category of headstamp. The batch numbers contained within this group appear to be consistent with the production period of Wide-I headstamps. This group appears tightly clustered which indicates there was little variation between the Wide-I headstamps. This could be explained by the relatively short time period in which this headstamp was used. It was possible that a single hob was used to produce all of the Wide-I bunters, resulting in all of the Wide-I bunters being essentially identical. This would result in the production of very similar headstamps apart from variation that was caused by wear on the hob and wear on the bunters. There were no records available to ascertain whether or not a single hob was used to produce all of the Wide-I bunters.

Another explanation for the tight grouping of the Wide-I headstamps could be related to a lower experimental error in gathering the data. Upon visual analysis of the Wide-I headstamps, in general the edges of the lettering appear very defined and can be easily determined. This is contrasted to that seen in the lettering of the Category 3 headstamps, where the detail of the edges of the lettering was often harder to define. Obviously, where the edges of the lettering can be easily defined there was reduced experimental error associated with processing the images and collecting data.

7.1.1.3 Group 3 (Category 4)

The headstamps on the cartridges contained within group 3 broadly correlated to Dr Sprott's Category 4 headstamp. The batch numbers contained within this group appear to be consistent with what is known about the period of production of Category 4 headstamps. There are interesting sub-groupings within this group. There appears to be at least two sub-groupings of the Category 4 headstamps, which probably relate to the Category 4a and 4b headstamps. There is also a possible third sub-grouping which lies between the upper and lower group. The appearance of the third sub-grouping within this headstamp category was unexpected as the previous exploration of the data did not identify this group. These possible sub-groupings were not discrete and there was considerable overlap between the postulated groups. Importantly however, the PCA biplot demonstrated that there was variation within the Category 4 headstamps and this variation may allow loose assignation of batches within this category depending on the date of manufacture.

7.1.1.4 Outlying Groups

The headstamps creating the small outlying data points at the top of group 1 were examined. These appeared to be similar to that of the Category 3 headstamps however they had substantially thinner lettering (Figure 7.2). One would expect headstamps that are seemingly similar to Category 3 headstamps, but with thinner letters, to be positioned above the Category 3 grouping in the PCA biplot. This could be deduced from the projected axes seen on the biplot. The projected axes relating to the width of the letters (*Width of "C"* and *Width of Right "I"*) were pointing down and slightly to the left. This meant that the headstamps which had thicker lettering were pushed in this direction within the reduced space of the PCA biplot. Conversely, headstamps with thinner lettering (as seen in the outliers) were pushed in the opposite direction (upwards and to the right). The Category 3 variants identified in the PCA biplot could be correlated to the sub-category of Category 3 headstamps that Dr Sprott identified and labelled Category 3b (see 1.1.2). Dr Sprott described the Category 3b headstamps as being similar to the Category 3 headstamps however the lettering was smaller [2, p31]. His description was slightly ambiguous as this could mean smaller in height or smaller in width of the lettering. Regardless, this small outlying group could have corresponded to this sub-category if Dr Sprott was referring to the thickness of the lettering in his description. Otherwise, the Category 3b headstamp that Dr Sprott referred to was not able to be identified in this analysis. Interestingly, the bivariate analysis performed by Dr Sprott and Professor Mowbray (Figure 1.5) also failed to identify the Category 3b headstamps. Apart from the first time Category 3b headstamps are mentioned by Dr Sprott (in his evidence for the 1980 Royal Commission of Inquiry), little else was said about this undefined category of headstamp.

Figure 7.2: Photographs comparing a Category 3 headstamp and a variant Category 3 headstamp. Left: An example of a Category 3 headstamp. Right: An example of a variant Category 3 headstamp which may be Dr Sprott's Category 3b headstamp.

There is also an interesting cluster of headstamps which reside below group 2 and to the right of group 3. The headstamps contained within this group appear to be similar, which suggests these are a genuine headstamp variant. The headstamps in this group were slightly similar to that of the Wide-I headstamps, however the letters seen in these headstamps were substantially wider and the edges of the lettering were less regular (Figure 7.3). The batches from which these headstamps came were fairly consistent with the period of production of Wide-I headstamps but there were some exceptions. Further, this variant headstamp was frequently encountered within boxes containing Wide-I headstamps. This suggests that this variant headstamp could have been the product of a very worn bunter or hob of the Wide-I design (NB: when bunters or hobs become worn, the thickness of the letters usually increases and the impressions produced in the headstamps become shallower). Conversely, this headstamp variant could also have resulted from a different hob being in operation at the same time that the Wide-I headstamp was in use.

Figure 7.3: Photograph of a variant of the Wide-I headstamp.

7.1.1.5 Bullet Distribution within the PCA Biplot

A PCA biplot of the dry-primed cartridges was used to assess the bullet-type distribution between the various groupings.

The same PCA biplot as shown in Figure 7.1 was used, but instead of labelling the observations by batch and sample number, there were coloured according to the bullet type observed in each cartridge.

Figure 7.4 shows the resultant bullet distribution within the sampled dry-primed cartridges. The groupings of headstamps have been labelled with the appropriate headstamp category and the observations have been labelled according to bullet type.

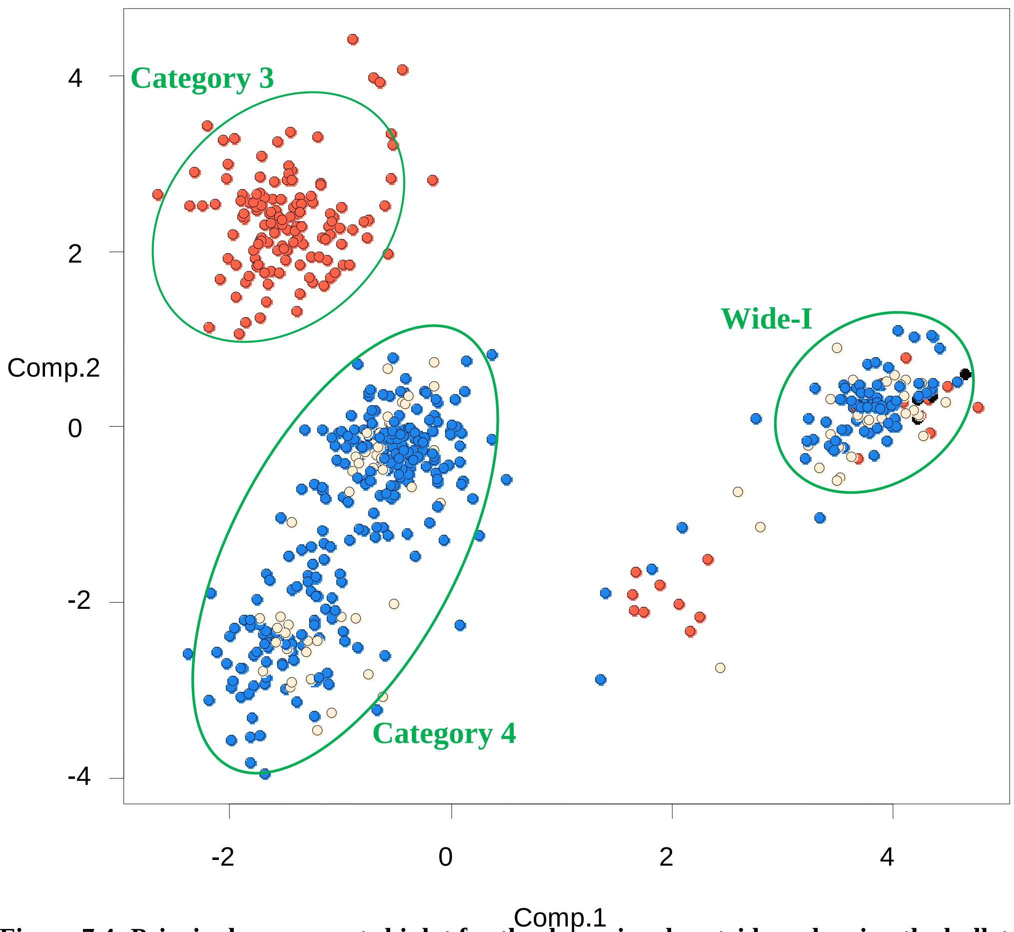


Figure 7.4: Principal components biplot for the dry-primed cartridges showing the bullet distribution within the groups. The observations have been coloured according to the bullet type observed in each cartridge. Pattern 8 bullet – Orange, Pattern 18 bullet – Cream, Pattern 19 bullet – Blue, Palma bullet – Black.

All of the Category 3 headstamped cartridges that were sampled were loaded with Pattern 8 bullets. The Wide-I headstamps were loaded with either a Pattern 8, 18, 19 or Palma bullet. This was expected as the Wide-I headstamp was in use during the time that the bullet machines were changed over from producing Pattern 8 bullets to the newer style Pattern 18 and 19 bullets. Additionally, the Wide-I headstamps were used on some military ammunition which were loaded with Palma bullets. The small loosely-spread cluster containing the Wide-I variant headstamps, seen between the Wide-I group and the Category 4 group, follow a similar pattern as the Wide-I headstamps. That is, the Wide-I variants contain either a Pattern 8 bullet or a Pattern 18 or 19 bullet. The majority of the observations that make up the Wide-I variant headstamps appear to have been loaded with Pattern 8 bullets, which suggests the Wide-I variant headstamps were produced early in the period in which the Wide-I headstamp was used (before the changeover to Pattern 18/19 bullets). Finally, the Category 4 headstamps (Category 4a and 4b) were loaded with either a Pattern 18 or a Pattern 19 bullet. There were no cartridges bearing Category 4a or 4b headstamps which were loaded with Pattern 8 bullets in the sampled data. This is what would be expected due to the changeover from producing Pattern 8 bullets to Pattern 18 and 19 bullets occurring before the Category 4 headstamps were used.

These findings corroborated Dr Sprott's observations regarding bullet type and headstamp category (see 1.1.2).

7.1.2 Hierarchical Clustering Analysis

A hierarchical clustering analysis was performed using the selected variables to see if more information could be gained from the data. The linkage criteria used in the analysis was complete linkage.

The dendrogram produced by the cluster analysis is shown in Figure 7.5. From first observation of the dendrogram there appears to be at least four major groupings of the data which are then sub-grouped accordingly. The major problem with the results from the cluster analysis is the massive overcrowding of the labels of the observations (batch numbers). This is due to the large number of observations that were used in the analysis. Understandably, gathering valuable information from the dendrogram in this format was impossible.

Various methods were trialled in an effort to make the results easier to interpret. One such method involved using "Figtree", a specialised graphical viewer for visualising dendrograms. However, all attempts failed to make the results from the hierarchical clustering analysis easier to visualize.

Although the groupings did show some promise, it was concluded that there were too many observations in the data for hierarchical clustering analysis to be used. Overall, it became too complicated to adequately interpret the dendrogram, making this statistical technique of little use to this project. For this reason hierarchical clustering analysis was not further pursued.

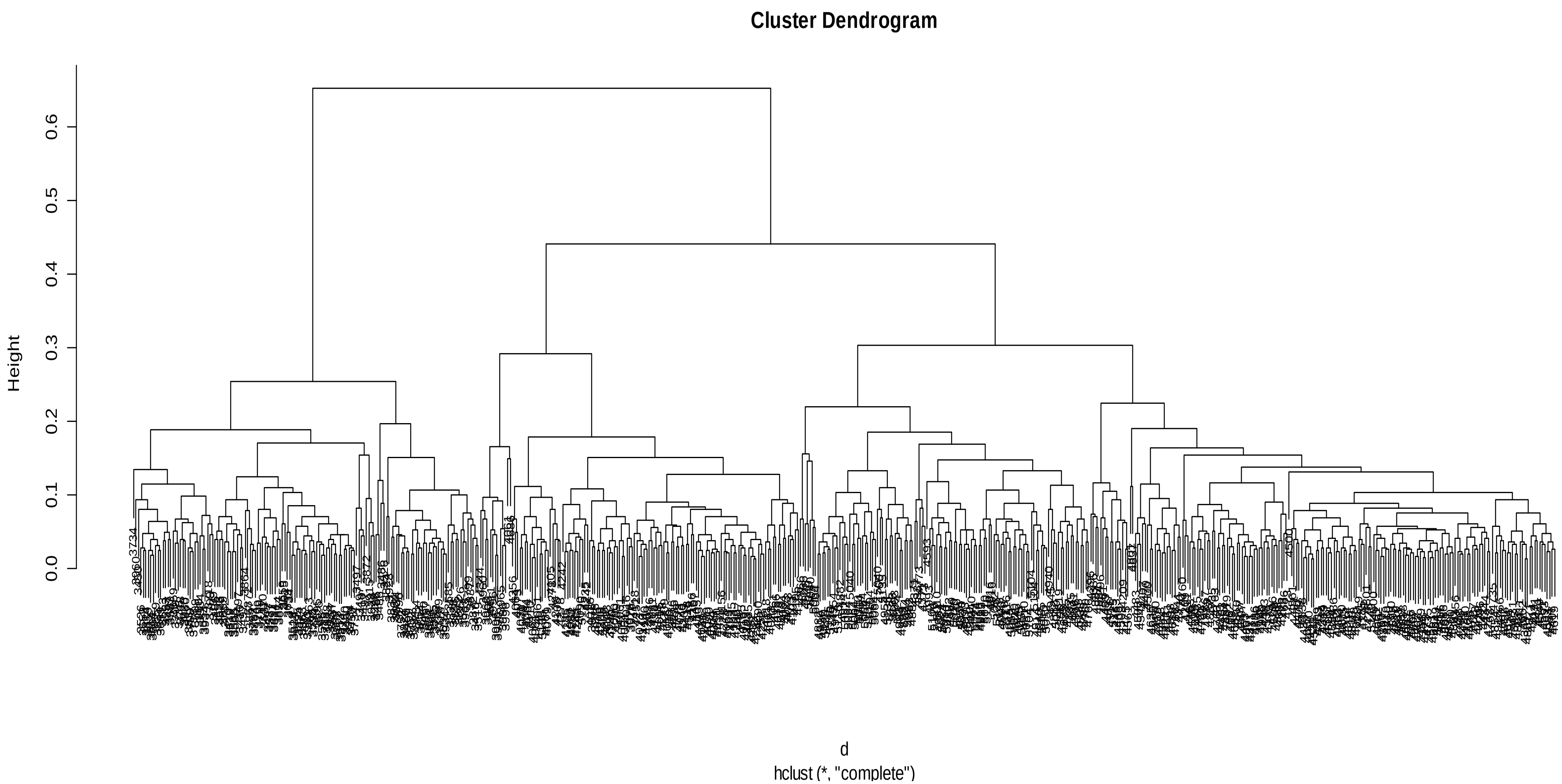


Figure 7.5: The resulting dendrogram from the hierarchical clustering analysis of the dry-primed cartridges.

7.1.3 Linear Discriminate Analysis

At this stage in the analysis the exploration of the data and the selection of the important variables had been completed. The PCA using the selected variables showed that there were underlying patterns in the data. The next step in the analysis was to build a model which was capable of classifying new unknown data. LDA was the statistical method used to do this. Later, this model would be used to classify a set of cartridges that formed a blind study and also to classify exhibit 350. However, first it was appropriate to assess the accuracy and the relative merits and weaknesses of the classification model using a cross-validation method.

7.1.3.1 Cross-Validation of the Data

The cross-validation method used to assess the classification model was a modified version of the “hold-out” method. Approximately five-sixths of the data was selected to be used as the training set in order to build the classification model. The training set was selected by taking five of every six samples (rounded down where appropriate) which had been collected from each batch. For instance, where six headstamps were sampled from a particular batch number, a random selection of five of these would be assigned to the training set. The remainder of the samples were held back from the model-building process (the testing set). After the model building had been completed, the testing set was introduced into the model as unknown data and the model was subsequently used to classify the unknown data into the most likely batch of origin.

When a prediction is performed using LDA, the LDA function actually produces the “posterior probability of group membership” [36]. In other words, LDA assesses the probability of obtaining the collected data given that the headstamp came from batch “x”. This is performed for all of the possible batches that the data could have came from (i.e. all of the batches that were represented in the training set). The final prediction of batch number comes from a “simple majority wins” classification rule where the batch which has the highest posterior probability is used as the prediction [36]. This process is repeated for each of the observations in the testing set.

7.1.3.2 Assessment of Correct Predictions

The predictions from cross-validation of the data are usually presented in a matrix which shows the true classification of each observation from the testing set versus all batch numbers. Due to the size of the table produced from cross-validation of the dry-primed data (109 rows by 109 columns), it was unable to be shown in this thesis. However, a small portion of a prediction table is shown in Table 7.1 (an example of a complete prediction table is provided in Appendix V).

		Testing Set									
		3410	**3450**	**3486**	**3497**	**3519**	**3526**	**3537**	**3553**	**3585**	**3595**
Predicted Batch Number	**3410**	0	0	0	0	0	0	0	0	0	0
	3450	0	1	0	0	0	0	0	0	0	0
	3486	0	0	1	0	0	0	0	0	0	0
	3497	0	0	0	1	0	0	0	0	0	0
	3519	0	0	0	0	0	1	0	0	0	0
	3526	0	0	0	0	0	0	1	0	0	0
	3537	0	0	0	0	1	0	0	0	0	0
	3553	0	0	0	0	0	0	0	1	0	0
	3585	0	0	0	0	0	0	0	0	0	0
	3595	0	0	0	1	0	0	0	0	0	0

Table 7.1: A small section of a prediction table produced from cross-validation of the data from the dry-primed cartridges.

To briefly explain the results in the table. The batch numbers from the headstamps used in the testing set are shown across the top of the table. The list of all possible batch numbers (for which the testing set could be predicted as having come from) is shown down the left side of the table. Within the table are the values of either "0" or "1". The value "1" shows where the relative predictions fell for each sample in the testing set. The total number contained in each column for the testing set represents how many cartridges were allocated into the testing set from each particular batch.

For instance, one of the headstamps that was from batch 3450, was used in the testing set and this was classified (predicted) as having come from batch 3450. In this instance the model has correctly classified the "unknown" data from the testing set into its true classification.

Another example shows that the headstamp from batch 3537 which was used in the testing set was predicted as having come from batch 3526 (as indicated by the "1" in the row corresponding to batch 3526). In this instance the headstamp from batch 3537 has been incorrectly classified as having come from batch 3526. This was an example of an incorrect classification, however it was important to appreciate that the prediction was very close to the true classification.

The column corresponding to batch 3497 has two entries where predictions have been made (one predicted as 3497, the other as 3595). This was not two separate predictions for a single headstamp, rather two headstamps from this batch have been allocated into the testing set. This was because there were ten cartridges sampled from batch 3497, where eight of these were allocated to the training set (five-sixths of ten which was rounded down to eight) and two of these were allocated to the testing set.

When prediction tables are presented in this format the correct classifications are contained within the diagonal of the table. Conversely, the incorrect classifications are contained in all cells apart from the diagonal. A rough measure of the success of the predictions can be obtained by counting the number of correct predictions and dividing this by the total number of predictions performed. An important factor to consider when assessing the success of the predictions in this way is that the relative classifications of the various cartridges changes each time an analysis is performed. This is due to the random nature of the selection of the training set and the testing set. Consequently, the calculated success of the predictions changes from analysis to analysis. To assess the overall success of the predictions, the analysis was repeated 200 times and the results were averaged.

The predictions had an average success of 12.6% (std-dev = 2). To put this into context, there were 108 cartridges in the testing set for each analysis and on average 14 (13.6) of these were correctly classified. This shows that the model performed poorly at classifying the data correctly into the exact batch of origin.

Using this method to assess the accuracy of the predictions is useful when true differences exist between all classes (batches) in the data. When considering the manufacturing procedure at ICI Australia it has to be acknowledged that the headstamps produced within a close time span are likely to be similar, even to the extent that they would be indistinguishable as far as the parameters measured in this project were concerned. This is due to the use of the same bunters, or bunters produced from the same hob. Accordingly, the headstamps on the cartridges received by CAC in each shipment were likely to be very similar. Shipments received by CAC were often used for weeks on end where each day one or two new batches of cartridges were produced. With respect to the manufacturing processes, one would not expect to see differences between the headstamps received in the same shipment. Further, differences between consecutive shipments may not be found unless this coincided with the production of a new hob or other process causing changes in the headstamps produced (e.g. substantial wear on a hob or bunter). With respect to these processes it is perhaps not surprising that the model performed poorly when classifying the testing set into the "exact" batch of origin. Further examination of the prediction tables showed that the predictions were usually within a close range of the true classification. For this reason, assessing the accuracy of the predictions by only taking into account the exactly correct classifications was not representative of the actual accuracy of the classification model.

7.1.3.3 Assessment of the Prediction Error

A much more suitable method for assessing the accuracy of the predictions was to use a prediction range, or to look at how far the predictions were from the true classification. This would give an indication of how close the true batch of origin was to the predicted batch of origin.

Two methods were considered for producing an output which showed the distance between the true batch number and the predicted batch number. These were as follows:

- Go through each sampled batch and re-number the batches so that they were relative only to the batches that were sampled. For instance, the first four batches which were sampled were 3410, 3450, 3486 and 3497. The batches would be renumbered so that; 3410 became 1, 3450 became 2, 3486 became 3 and 3497 became 4. This way the predicted batch could be subtracted from the true batch in order to assess how far the prediction was from the true batch number, relative to the batches which had been sampled.
- Conversely, leave the batches as they were and simply subtract the predicted batch from the true batch in order to assess the how far the prediction was from the true batch.

Each method had flaws. The first method failed to take into account the relative distance between the batches which had been sampled in this project. For some areas of the sampling range there were relatively large distances between batches and for other areas there were small distances. For instance, the largest distance between two consecutively sampled batches was 64 batches and the smallest distance was one batch. Using this method did not give any indication of the actual distance between the batches, instead it was only relative to the batches that were sampled in this project.

The second method simply used the difference between the true batch number and the predicted batch. The sampling range selected for this project contained approximately 1800 batch numbers, ranging from batch 3410 to 5211. Within the batch number range there were also a large number of batches of ammunition that were not relevant to this project (e.g. Short cartridges, Shots, Copper-cased cartridges and Nickel-cased cartridges). Altogether there were 540 (approximately 1/3) batches of irrelevant ammunition that were produced intermittently between the relevant batches for this project. This second method did not take into account the irrelevant batches that may have been produced between the actual batch and the predicted batch.

The second method was chosen. Since it used the raw batch numbers, it is important to understand that this method resulted in an overstated distance between the true batch and the predicted batch (i.e. an overstated prediction error). It was possible to sift through the CAC production records to remove the irrelevant batch numbers, however it was decided to accept that this error existed and keep the integrity of the actual batch numbering.

The analysis was repeated 200 times with the relative distance between the actual batch and the predicted batch for each prediction averaged. The resulting graph is shown in Figure 7.6.

A further graph showing the average prediction error with a 95% confidence interval of the predictions is shown in Figure 7.7.

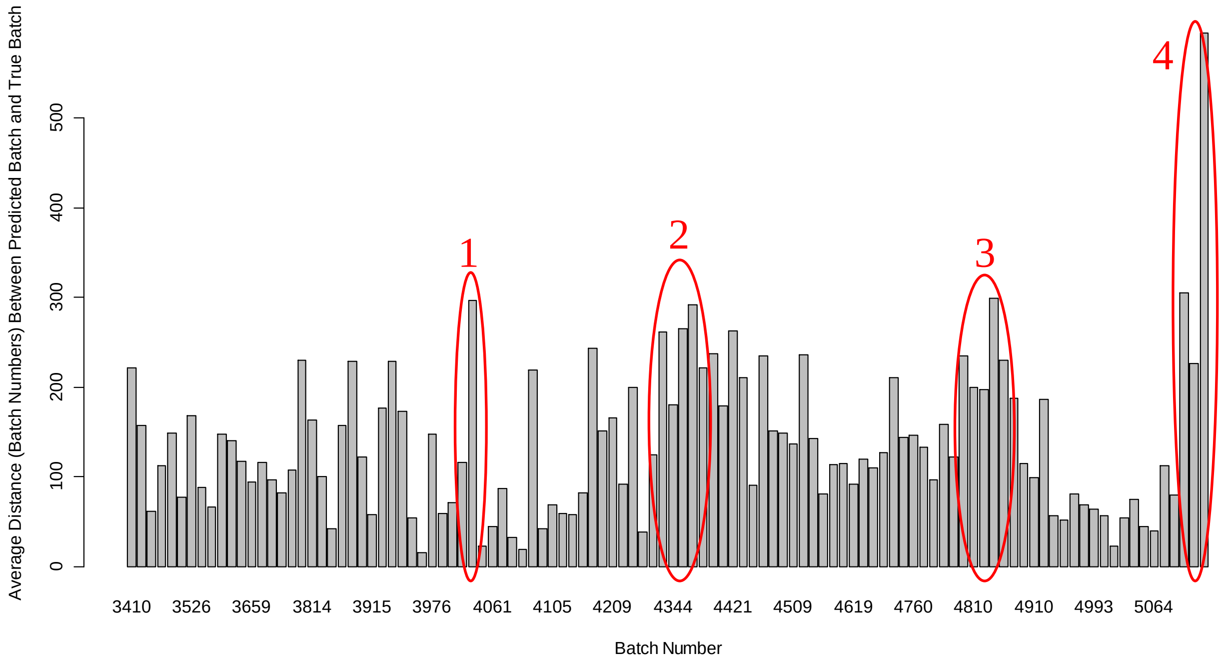


Figure 7.6: Histogram of the prediction error for cross-validation of the dry-primed cartridges. The average prediction error is plotted against the batch numbers of the dry-primed cartridges from the testing set.

Due to the large number of batch numbers represented in the testing set, every column on the x axis was unable to be labelled with the corresponding batch. Instead, every 6th column on the x axis has been labelled.

Each of the columns in the graphs (Figure 7.6 and 7.7), corresponds to the following batches from the testing set;

3410, 3450, 3486, 3497, 3497, 3519, 3526, 3537, 3553, 3585, 3595, 3659, 3659, 3709, 3718, 3734, 3752, 3799, 3814, 3824, 3837, 3857, 3864, 3872, 3915, 3928, 3934, 3960, 3963, 3965, 3976, 3996, 3996, 4016, 4031, 4061, 4061, 4064, 4073, 4079, 4090, 4103, 4105, 4118, 4140, 4156, 4185, 4209, 4209, 4235, 4242, 4252, 4278, 4296, 4344, 4356, 4371, 4407, 4411, 4419, 4421, 4463, 4470, 4475, 4483, 4500, 4509, 4538, 4549, 4561, 4561, 4593, 4619, 4635, 4661, 4662, 4686, 4735, 4760, 4763, 4766, 4766, 4773, 4801, 4810, 4837, 4837, 4854, 4867, 4882, 4910, 4914, 4916, 4940, 4945, 4954, 4993, 5010, 5024, 5040, 5052, 5064, 5064, 5104, 5116, 5125, 5135 and 5149.

(NB: some batches were represented twice in the testing set due to increased numbers of samples from these batches)

Figure 7.6 shows that in general the predictions were relatively close to the actual classifications of the observations used in the testing set. Around 83% of the averaged predictions were less than 200 batch numbers from the actual batches. On average, each prediction that was made was around 138 batch numbers away from the actual batch number of the observation. 138 batch numbers corresponds to a production period of approximately six months. This shows the classification model was very accurate at classifying the cartridges into a defined time period.

Some important features of the graph (Figure 7.6) have been highlighted and will be discussed.

The prediction error labelled “1” corresponds to the headstamps from batch 4031 (Figure 7.6). The average prediction error for this batch was around 288 batch numbers which was relatively high and the 95% confidence interval of the predictions was very wide (Figure 7.7). The headstamps sampled from this batch were a mixture of Wide-I and Category 4a headstamps. The presence of Wide-I headstamps in this batch was not unusual as this was the prominent headstamp in use around this time of production. However, the presence of Category 4a headstamps was peculiar as these headstamps were not seen prominently until after batch 4290. This suggests that the box of ammunition sampled from this batch could have contained cartridges of impure provenance as the presence of Category 4a headstamps this early in production is unlikely. The presence of Category 4a headstamps within the sampled box of ammunition led to an increased average prediction error, because when the Category 4a headstamps were randomly assigned into the testing set (prediction set) the LDA model predicted these as having come from a much later period of production (i.e. after batch 4290).

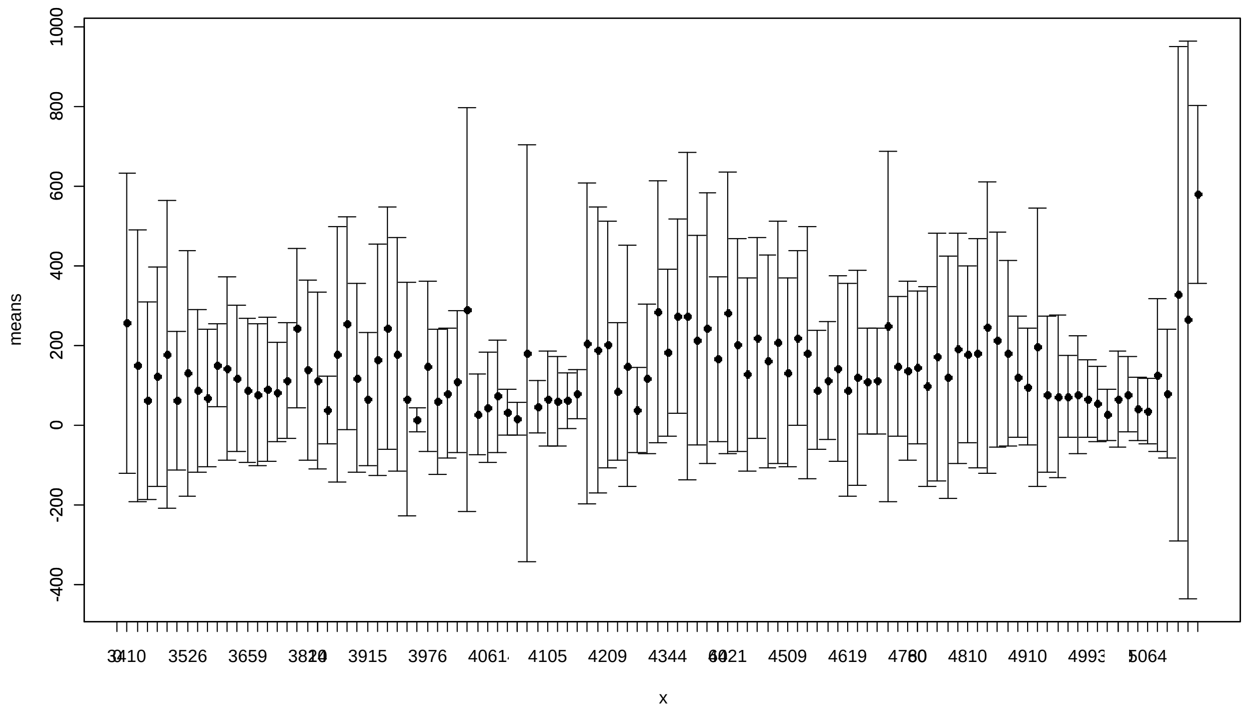


Figure 7.7: Whisker plot of the average distance between the actual batch number and predicted batch number for the cross-validation of the dry-primed cartridges (showing the 95% confidence interval of the predictions).

The area on the graph labelled “2” shows an increased average prediction error (Figure 7.6). This period loosely corresponds to when the changeover from Wide-I headstamps to Category 4a headstamps occurred. From the manufacturing processes at ICI Australia and the relative mixing of the headstamps during packaging and shipping, it is perhaps not surprising that many of the boxes of ammunition around this time period contained mixes of Wide-I and Category 4a headstamps. In the same way that mixed headstamps in batch 4031 provided increased average error of predictions, it is likely that this same mechanism is responsible for the increased average prediction errors seen for these batches. Similarly, the area on the graph labelled 3 corresponds to the changeover between the Category 4a headstamps to the Category 4b headstamps (Figure 7.6). In these batches of cartridges there is substantial mixing of Category 4a and 4b headstamps. Once again the same mechanism is probably responsible for the small spike in prediction errors seen in this area.

The group labelled 4 on the graph corresponds to batches 5125, 5135 and 5149 (Figure 7.6). The headstamps sampled from batch 5125 were composed of a mixture of Wide-I and Category 4b headstamps. It was this mix of headstamps which created the increased average error of the predictions. The 95% confidence interval of the predictions for this batch was very wide indicating that the predictions spanned a wide range (Figure 7.7). The upper range of the confidence interval lies at around 900 (e.g. a difference of 900 batches between the actual batch and the true batch). A prediction of 900 batches from the actual batch (5125) corresponds to predictions of around batch 4100, which is about the time period that Wide-I headstamps were used. The same patterns in the graphs were seen for batch 5135. Upon further analysis of the headstamps sampled from this batch, they too appear to be a mix of Category 4b headstamps and Wide-I headstamps. The appearance of Wide-I headstamps this late in production was unexpected and could indicate that these boxes (from batches 5125 and 5135) contained cartridges of impure provenance. However, it is possible that this mixing was genuine and could have arisen from production processes at CAC or ICI Australia (e.g. finishing off an old shipment of cartridges that was received when the Wide-I headstamp was in use or the use of an old Wide-I bunter) but this was very unlikely.

The largest outlier on the graph came from the batch 5149 (Figure 7.6). The box of ammunition sampled from this batch was composed mainly of wet-primed cartridges (five of which were sampled and subsequently used in the wet-primed analysis) and six dry-primed cartridges, (one of which was sampled). The dry-primed cartridge which was sampled from this batch appears to have a Category 4a headstamp. The CAC production records state that this batch (5149) used wet-primed cartridges, hence the dry-primed cartridges present in this box are almost certainly not original. For this reason the extremely high prediction error associated with this batch was assumed to be spurious and can be ignored.

Various other outliers were also examined and the general conclusion drawn was that the batches which had higher average prediction errors and large conference intervals were composed of cartridges which had mixed categories of headstamps (whether this was due to cartridges of suspected impure provenance, genuine headstamp mixing from manufacturing processes or random headstamp variants that occurred from time to time). Taking into account the boxes of mixed headstamps, the accuracy of the classification model was impressive. This meant that the classification model could be very useful for determining the production period in which an unknown cartridge was produced. The accuracy of the model was further tested in a blind study (see Chapter 8).

7.2 WET-PRIMED CARTRIDGES

Exploration of the data collected from the wet-primed cartridges suggested that there were three main variants of the headstamps. The first of these was the Tenex headstamp which was seen between batches 4019 and 4022 and again between 4049 and 4050 (see 2.3.3). The appearance of Tenex headstamps within these batches was consistent with the CAC production records.

The second headstamp variant seen was the headstamp of English manufacture (see 2.3.3). This was similar to the Tenex headstamp (both had square-ended lettering), however the letters in this headstamp were much thinner. The headstamp of English manufacture was seen in boxes of Imperial brand ammunition (batches 4845 to 4849 and 4919 to 4927) and also in a box of Mark10 rejects (batch 4862). Each box that contained this headstamp also contained cartridges bearing the Category 4c headstamp, however these were genuine mixes and were the result of production processes at CAC.

The major headstamp variant that was seen in the wet-primed cartridges was a variant of Dr Sprott's Category 4 headstamp, which was labelled Category 4c. This headstamp was seen in conjunction with the headstamps of English manufacture in the Imperial brand ammunition (batches 4845 to 4849 and 4919 to 4927) and in a batch of the Mark10 reject ammunition (batch

4862). In a different batch of Mark10 rejects (4953), this headstamp was seen exclusively. This headstamp was seen in the box of probable impure provenance (batch 4766) and was also seen exclusively in batches 5149 to 5211. Interestingly, the data exploration of the wet-primed headstamps indicated that the Category 4c headstamps may be further sub-grouped into different categories.

The data transformations which appeared to be having the largest influence on the headstamps from the wet-primed cartridges were identified in the graphs produced in 6.4.2. Various combinations of the data transformations were used for statistical analysis of the wet-primed cartridges in order to define which variables would give the best separation of the respective groups. The results from the various statistical analyses were subjectively judged by which analysis gave the best separation of the groups. The results from LDA were further judged objectively by which combination of variables provided the lowest error of prediction from cross-validation of the data.

Similarly to what was performed for the dry-primed cartridges, some additional variables were produced by combining tightly correlated variables. Additionally, some of the original standardised coordinates were identified as having a large influence on the data and these were subsequently used in the various analyses.

The following variables appeared to be offering the greatest discrimination between the batches of wet-primed cartridges and were used in the following statistical analysis.

- *Sum of Letter Heights*
- *Sum of Letter Widths*
- *Horn Distance*
- *Edge of Left "I" to Edge of "C"*
- *Edge of "C" to Edge of Right "I"*
- *Left "I" Skeleton to "C" Skeleton*
- *15y*
- *16x*
- *16y*

(NB: *15x*, *16x* and *16y* correspond to the original collected coordinates after they had been subject to the standardising transformation (see 4.9.3)).

7.2.1 Dimension Reduction by PCA

From analysis of the PCA summary it was determined that a biplot of the first two principal components (Figure 7.8) would give a fair representation of the data set, as these together explained around 85% of the variance in the data.

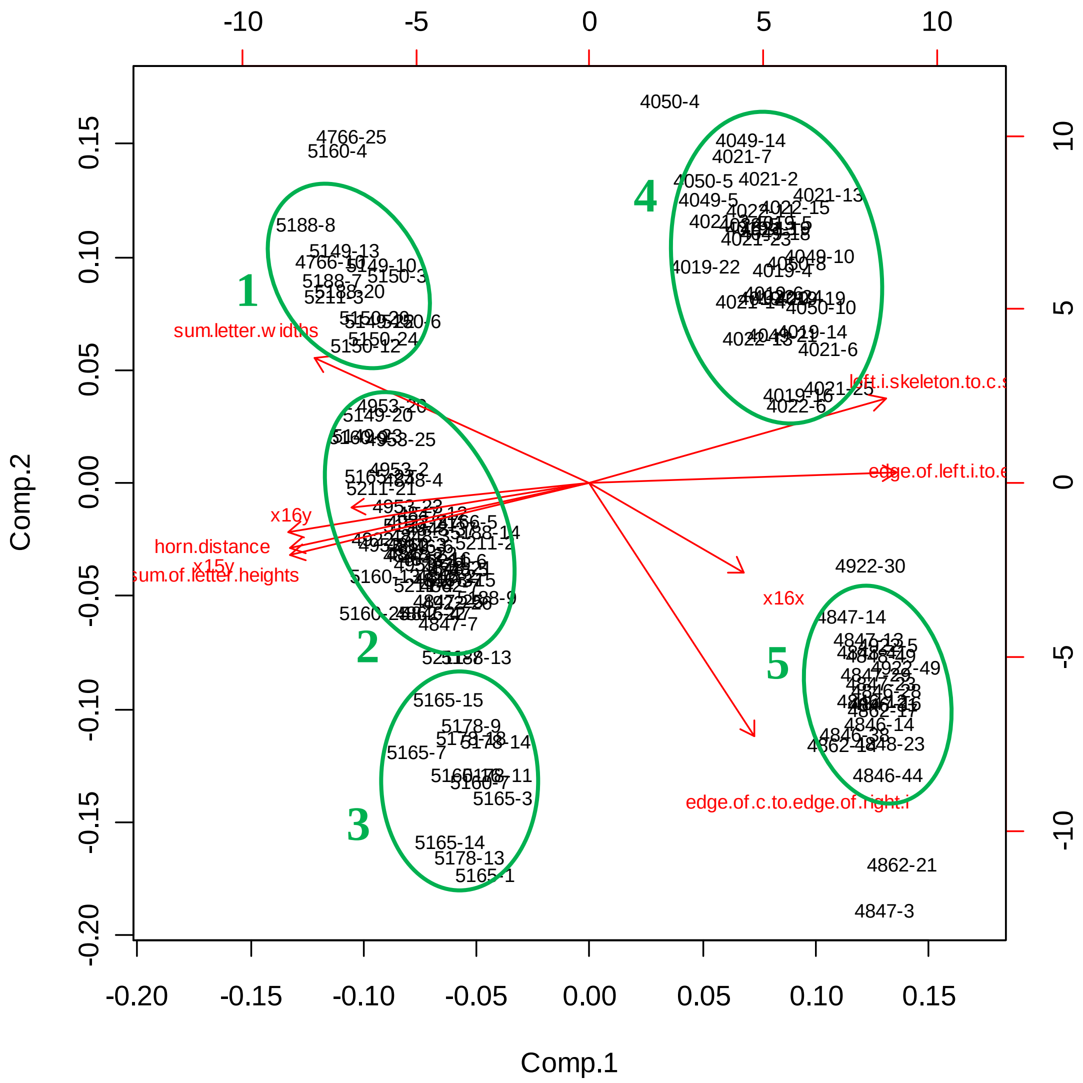


Figure 7.8: Principal components biplot for the nine selected variables from the wet-primed cartridges.

There appears to be five main groups within the PCA biplot which have been labelled 1 to 5 (Figure 7.8).

The groups which lie to the right side of the biplot (groups 4 and 5) are composed of the headstamps with the square-ended lettering (Tenex and headstamps of English manufacture). The groups which lie to the left side of the biplot (Groups 1, 2 and 3) are composed of the Category 4c headstamps

7.2.1.1 Groups 1, 2 and 3 (Category 4c)

Groups 1, 2 and 3 contain data from the Category 4c headstamps. The formation of three groups containing this category of headstamp supports the proposition that the Category 4c headstamps can be divided into several sub-variants of headstamp. However, there is some overlap between the groups which reflects how closely related the headstamps are.

Group 1 appears to contain mainly headstamps from batches 5149, 5150, 5160 and 5188. This group also contains the headstamps from the cartridges from batch 4766, which have been identified as being of probable impure origin. The headstamps in group 1 appear to have slightly thicker lettering that the other Category 4c headstamps.

Group 2 is an interesting group which contains headstamps from a range of batches. The headstamps from the Category 4c cartridges found in the Imperial brand ammunition are found in this group (batches 4846, 4847, 4848 and 4922), along with some of the wet-primed cartridges which were produced towards the end of the use of the sans-serif-ICI headstamp (around batches 5150-5211) and the headstamps from a box of Mark10 reject ammunition (batch 4862). There is considerable spread within the group 2 headstamps and it is uncertain whether these are true differences or simply the result of experimental error. The headstamps contained within this group appear to be similar to that contained in group 1, but with slightly thinner lettering.

The headstamps in group 3 are similar to those contained in groups 1 and 2, however the lettering of these headstamps appears thinner. The headstamps in group 3 appear to have come exclusively from batches 5160, 5165 and 5178.

Although the Category 4c headstamps appear to be divided into at least three sub-variants of headstamp, the variants appear to be found together in multiple batches. This is indicated by various batches of cartridges being represented in multiple groups. For instance, the headstamps from batch 5160 are represented in groups 1, 2 and 3. Generally, the appearance of mixed headstamps within a box of ammunition would be indicative that the box contains cartridges of impure provenance. However, the appearance of mixed headstamps in nearly all of the wet-primed batches produced after 5149 suggests that these mixes are probably genuine. This indicates that it was likely that multiple headstamp variants were in use at a single time.

7.2.1.2 Groups 4 and 5 (Tenex and English manufacture)

Groups 4 and 5 contain the headstamps with characteristic square-ended lettering. Due to the obvious differences between these headstamps and the other headstamps of the wet-primed cartridges (Category 4c) it was not surprising that these two groups were well separated from the others. Group 4 contained the Tenex headstamps and Group 5 contained the headstamps of English manufacture from the Imperial brand ammunition. The Imperial brand ammunition contained genuine mixes of headstamps, with the other headstamps from these batches being represented in group 2. The outliers that can be seen below group 5 appeared to have very similar headstamps to those contained in group 5. Their position is likely to result from increased experimental error due to the irregular edges of the headstamps causing scattering of the data. The headstamp on the outlier that lies above group 1 (4050-4) did not appear to be too dissimilar from the Tenex headstamps contained within the majority of the group. There was however some wear on the headstamp, causing the lettering to become slightly thicker which could have caused this headstamp to be placed as a slight outlier

7.2.1.3 Bullet Distribution within the PCA Biplot

The PCA biplot from the wet-primed cartridges was used to assess the bullet-type distribution between the various groupings of headstamps (Figure 7.9).

This was performed by using the same PCA biplot as shown in Figure 7.8, but instead of labelling the observations by batch and sample number, they were coloured according to the bullet type observed in each cartridge. The groups within the biplot have been labelled according to the type of headstamp found within the groups.

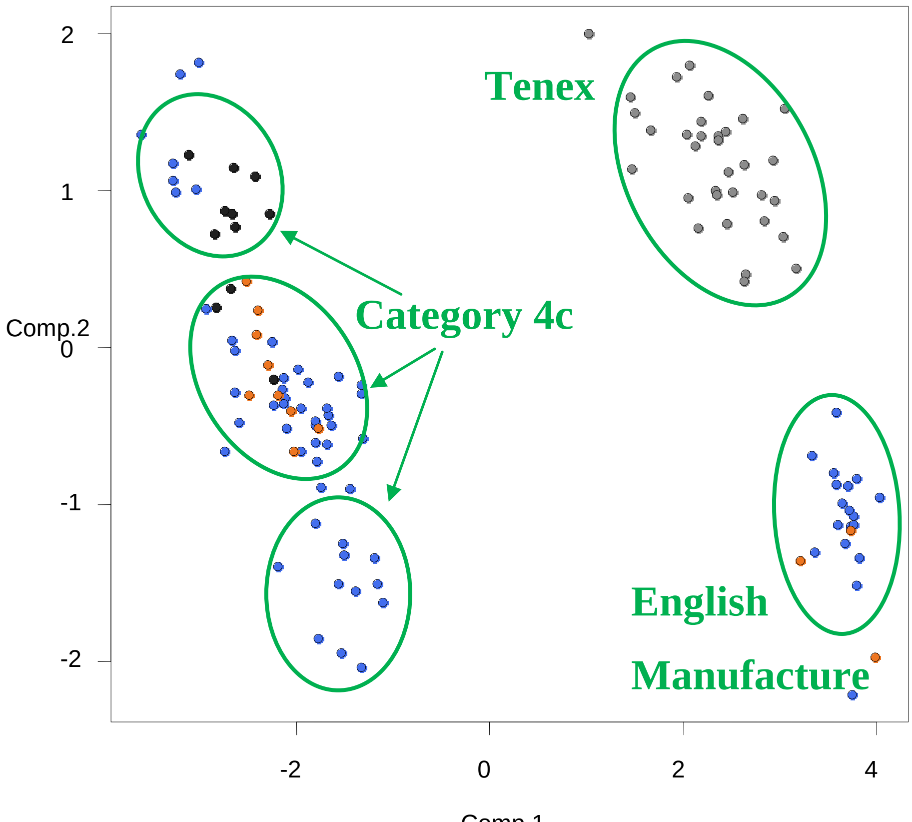


Figure 7.9: Principal components biplot for the wet-primed cartridges showing the bullet distribution within the groups. The observations have been labelled according to bullet type observed in each cartridge. Palma bullet – Grey, Pattern 18 bullet – black, Pattern 19 bullet – blue, Pattern 20 bullet – orange.

The Tenex cartridges were produced during the time period when the Pattern 8 bullets were the main bullet type used by CAC, however all of the Tenex cartridges were loaded with Palma bullets. This was not surprising as the Tenex cartridges were mainly used for military ammunition and military ammunition was almost always loaded with Palma bullets. All of the other wet-primed cartridges were produced after the changeover from Pattern 8 to Pattern 18 and 19 bullets, therefore it was not surprising that the main bullet types seen in these were the Pattern 18 and 19 bullets. There were also some Pattern 20 bullets seen in the middle grouping of Category 4c headstamps. The cartridges which were loaded with Pattern 20 bullets were from the Mark10 reject batches. The Mark10 cartridges were loaded exclusively with Pattern 20 bullets.

7.2.2 Hierarchical Clustering Analysis

Hierarchical clustering analysis was a more useful tool when dealing with the reduced number of observations with the wet-primed cartridges. However, as this statistical tool was unable to be used on the dry-primed cartridges it was deemed unnecessary to be used with the wet-primed cartridges. For this reason no analysis and discussion was conducted on the wet-primed cartridges using this technique.

7.2.3 Linear Discriminate Analysis

The next step in the analysis was to build a model which was capable of classifying new data. LDA was used to build this model. This model was subsequently used to classify headstamps from wet-primed cartridges in a blind study. However, first it was necessary to assess the accuracy and the relative merits and weaknesses of the classification model using a cross-validation method.

7.2.3.1 Cross-Validation of the Data

A similar cross-validation method to that used for the dry-primed cartridges was performed on the wet-primed cartridges. Due to the reduced number of observations in the wet-primed analysis, it was decided that two-thirds of the samples from each batch would be used for training the model, with the remaining one-third used for predictions (compared to 5/6 for the dry-primed training set).

7.2.3.2 Assessment of Correct Predictions

A typical prediction table from one of the cross-validations performed on the data from the wet-primed cartridges is shown in Table 7.2.

For information regarding the interpretation of these tables see 7.1.3.2.

Cross-validation of the data was repeated 200 times and with each analysis the number of correct classifications (in the diagonal of the table) was recorded. The number of correct classification in each analysis was subsequently used to calculate the average success of the predictions in terms of classifying the data into the correct batch of origin. On average 29% (std-dev = 5) of the predictions were correctly classified. To put this into context, there were 45 cartridges in the testing set in each analysis and on average 13 of these were classified into the correct batch of origin. The classification model for the wet-primed cartridges appeared to be more successful than that seen for the dry-primed cartridges. However this was likely to be due to there being considerably less observations in the wet-primed model and therefore the likelihood of obtaining correct classifications was increased.

It was acknowledged that assessing the accuracy of the classification model using this measure was not representative of the actual accuracy due to the similarities in the headstamps found in closely related batch numbers (as discussed in 7.1.3.2). The prediction tables for the cross-validations of the data (e.g. Table 7.2) showed that in general, where the predictions were incorrect, they were still very close to the true batch of origin.

		Testing Set																		
		4019	**4021**	**4022**	**4049**	**4050**	**4766**	**4846**	**4847**	**4848**	**4862**	**4922**	**4953**	**5149**	**5150**	**5160**	**5165**	**5178**	**5188**	**5211**
Predicted Batch Number	**4019**	3	2	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	4021	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	4022	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	4049	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	4050	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	4766	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
	4846	0	0	0	0	0	0	1	2	1	1	0	0	0	0	0	0	0	0	0
	4847	0	0	0	0	0	0	1	1	1	0	1	0	0	0	0	0	0	0	0
	4848	0	0	0	0	0	0	1	0	2	1	1	0	0	0	1	0	0	0	0
	4862	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	4922	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
	4953	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
	5149	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	1	0
	5150	0	0	0	0	0	0	0	1	0	0	0	0	1	2	0	0	0	0	0
	5160	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	5165	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0
	5178	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0
	5188	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1
	5211	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1

Table 7.2: A prediction table from cross-validation of the data from the wet-primed cartridges.

7.2.3.3 Assessment of the Prediction Error

Finding a method for assessing the accuracy of the wet primed model was difficult due to the scarcity of the wet-primed batches of cartridges that were produced. The batches of wet-primed cartridges appeared to be produced for short periods intermittently throughout the production period of interest to this project [5].

A similar method to that conducted for the dry-primed cartridges was used to assess the accuracy of the predictions. The relative accuracy of the predictions was determined by finding the difference between the true batch and the predicted batch. The cross-validation of the data was repeated 200 times and the accuracy of the predictions (in terms of the relative distance between predicted batch and true batch) were averaged. This had some problems as there were extended periods of production where no wet-primed cartridges were produced. This meant that a prediction that was hundreds of batch numbers away from the true batch of a cartridge, could have actually been much closer when only the wet-primed batches were considered. For this reason, it is important to understand that assessing the error of the predictions using this method resulted in an overstated prediction error.

The graph showing the average distance (in terms of batch numbers) between the true batch and the predicted batch for each prediction made in the cross-validation of the data (200 repeats) is shown in Figure 7.10.

A further graph showing the average prediction error with a 95% confidence interval of the predictions is shown in Figure 7.11.

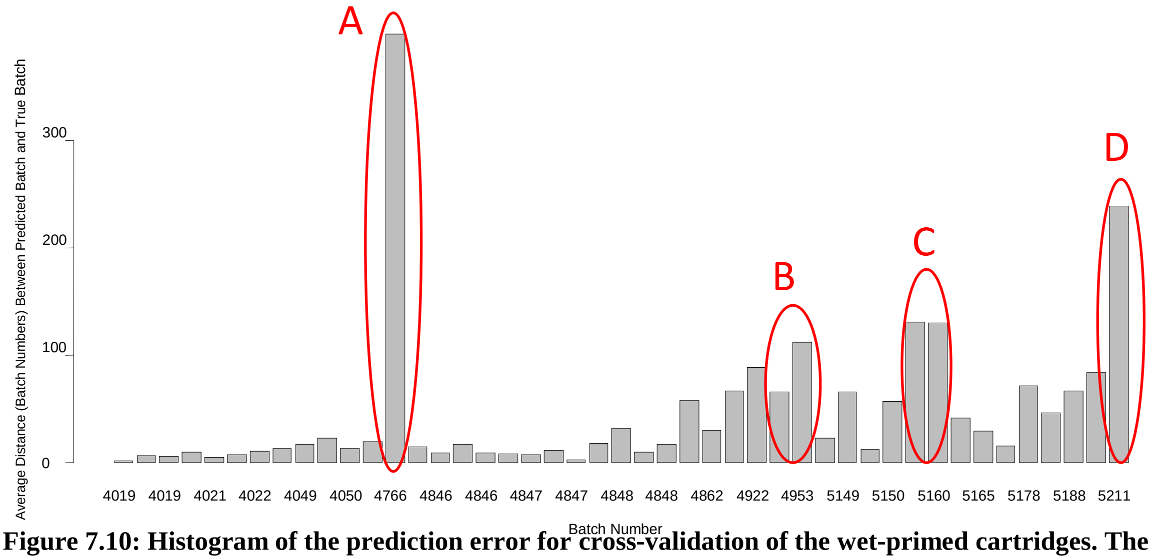


Figure 7.10: Histogram of the prediction error for cross-validation of the wet-primed cartridges. The average prediction error is plotted against the batch numbers of the wet-primed cartridges from the testing set.

Due to the large numbers of observations represented in the testing set, every column on the x axis was unable to be labelled with the corresponding batch. Instead, every 2nd column on the x axis has been labelled.

Each column in the graph (Figure 7.10), corresponds to the following batches that were represented in the prediction set;

4019, 4019, 4019, 4021, 4021, 4021, 4022, 4022, 4049, 4049, 4050, 4050, 4766, 4846, 4846, 4846, 4846, 4847, 4847, 4847, 4847, 4848, 4848, 4848, 4848, 4862, 4862, 4922, 4922, 4953, 4953, 5149, 5149, 5150, 5150, 5160, 5160, 5165, 5165, 5178, 5178, 5188, 5188, 5211 and 5211. (NB: from each batch there were multiple cartridges allocated into the testing set due to how the testing and training sets were allocated).

Figure 7.10 shows that in general the predictions were very close to the true batch. The relative distance (in terms of batch number) between the predicted batch and the true batch was rarely more than 100 batches. This shows that the model performed very well at classifying the wet-primed cartridges. On average, each prediction that was made was 46 batches away from the true classification of the cartridge.

The predictions concerning the batches of ammunition containing the Tenex cartridges (4019-4050) were shown to be very accurate. There was a very low average prediction error for the Tenex batches with a very narrow 95% confidence interval for the predictions (Figure 7.11). Further observation of some of the prediction tables showed that although the predictions for the

Tenex cartridges were often wrong, they were always predicted as coming from other Tenex batches. Due to the short time period in which the Tenex batches were used, this resulted in a low average prediction error. This was perhaps not surprising due to the large class differences between the Tenex headstamps and the other wet-primed headstamps.

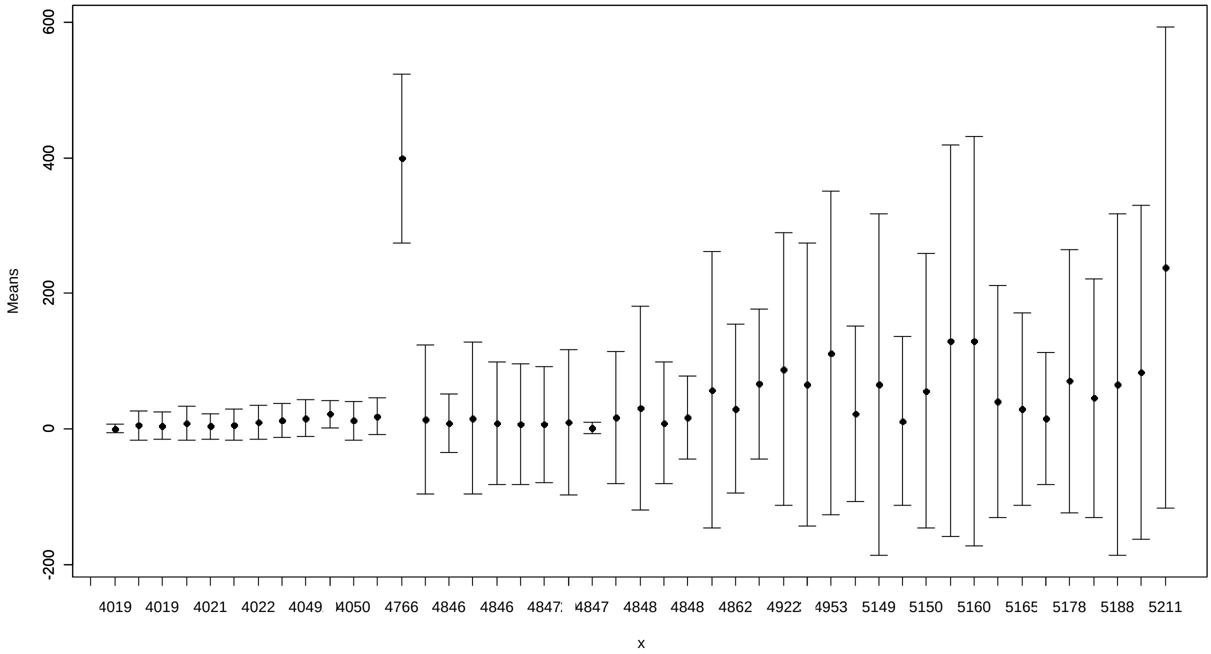


Figure 7.11: Whisker plot of the average distance between the actual batch number and the predicted batch number for the cross-validation of the wet-primed cartridges (showing the 95% confidence interval of the predictions).

The predictions concerning the cartridges from the Imperial brand ammunition (4845-4849 and 4919-4927) also appear to be very accurate as shown by the low average error of the predictions and narrow 95% confidence interval (Figures 7.10 and 7.11). This was interesting as these boxes contained mixtures of the headstamps of English manufacture and the Category 4c headstamps, both of which were sampled in this project. It is understandable that when the headstamps of English manufacture were allocated into the testing set, the prediction error would have been low. This is because these headstamps are found almost exclusively within Imperial brand ammunition hence the predictions would have been exactly correct or very close to the true batch (i.e. other Imperial batches). However, the Category 4c headstamps in these boxes appear similar to the headstamps seen in other wet-primed batches of ammunition produced after the Imperial batches (i.e. batches 4953 to 5211). The fact that the average prediction error for the Imperial batches is low and that the 95% confidence interval for the predictions is narrow (Figure 7.11), could suggest that the Category 4c headstamps within the Imperial brand batches were different from the Category 4c headstamps that occurred in later batches. This would support the theory that the Category 4c headstamps were further sub-divided into other separate variants of headstamp. For this reason, the Category 4c headstamps that are seen within the boxes of Imperial brand ammunition have been labelled Category 4c-1 (Figure 7.12).

Figure 7.12: The variant of the Category 4c headstamp (Category 4c-1) found within the Imperial brand boxes of ammunition.

Some other interesting features in Figure 7.10 have been labelled A to D.

The prediction error labelled A corresponds to batch 4766. The provenance of this box has already been questioned during the exploration of the wet-primed data (see 6.4.2) as this batch contained a mixture of wet and dry-primed cartridges which had not been referenced in the CAC production records. The extremely high prediction error for this batch (approximately 400 batches) probably results from the wet-primed cartridges within this box being of impure provenance. This was further reflected by the relatively narrow 95% confidence interval of the predictions (approximately 100 batches either side of the average) seen in Figure 7.11. This indicated that the predictions for the wet-primed cartridges within this box were consistently around 300 to 500 batches away from batch 4766. This shows that the wet-primed cartridges within the sampled box were consistently classified as originating from a batch produced between about 5066 and 5266. This suggests that these cartridges were probably originally contained within a box of ammunition produced between batches 5066 and 5266, after which they were removed and added to the sampled box from batch 4766.

The group labelled B corresponds to batch 4953, which was a batch of Mark10 reject cartridges. The average prediction error for the cartridges within this batch was relatively high. Upon further analysis of the sampled cartridges, the headstamps seem to fall into Category 4c however there are slight differences between the letter thicknesses possibly indicating variants of the Category 4c headstamp. It was the mixed nature of the headstamps in this box which caused a slight increase in the prediction errors observed for these cartridges. It is perhaps not surprising that this box contains a possible mix of headstamps given their description in the CAC records as Mark10 rejects. During the production of Mark10 accuracy cartridges, they were assessed to ensure that the cartridges were of sufficient quality to be used in Mark10 boxes of ammunition. In instances where the cartridges were deemed to be unsatisfactory, these were put aside. This occurred over many batches until sufficient numbers of Mark10 reject cartridges were gathered. Once a sufficient number of reject cartridges had been gathered, they were exhausted by producing a whole batch, or batches, of Mark 10 reject cartridges. It is understandable that these batches of ammunition could contain mixes of various headstamps which had been used over an extended period.

The groups labelled C and D correspond to batches 5160 and 5211 respectively. These were interesting batches of cartridges that appeared to contain a mix of at least three variants of the Category 4c headstamp as shown in Figure 7.13. These Category 4c variants have been labelled Category 4c-2, Category 4c-3 and Category 4c-4 respectively. Interestingly, these Category 4c variants appear to be slightly different to the variants seen in the Imperial boxes of ammunition which have been labelled Category 4c-1 (Figure 7.12). This suggests that there were at least four closely related variants of the Category 4c headstamp which were used on wet-primed cartridges. Further analysis of the wet-primed batches produced between 5149 and 5211, showed the appearance of mixtures of Category 4c-2 and 4c-4 cartridges was common. However, the appearance of Category 4c-3 headstamps was characteristic for batches 5160 and 5211. As these batches had higher prediction errors than the other batches containing mixed headstamps, it is possible that the presence of this variant headstamp (Category 4c-3) could have been causing the increased prediction error. In batches 5149 and 5211 there was only one Category 4c-3 headstamp sampled from each batch with the remainder of those sampled bearing Category 4c-2 and 4c-4 headstamps. The presence of only one Category 4c-3 headstamp in each box caused problems during the training and testing of the classification model. Understandably, when the data from the Category 4c-3 headstamp was allocated to the testing set, this resulted in no Category 4c-3 headstamps being used in the training set. This meant that no classifier for this headstamp was learnt by the classification model. This was not such a problem when either batch 5160 or 5211 had a Category 4-c3 represented in the training set. However, in instances where the Category 4-c3 headstamp from both of these batches was represented in the testing set, the cartridges were predicted as having come from batch 4766 (NB: the wet-primed cartridges from this batch are almost certainly of impure provenance). This suggests that the cartridges in batch 4766 had headstamps that were the same as or very similar to Category 4-c3 headstamps. It was these predictions which caused the increased average prediction error and the wide 95% confidence intervals of the predictions for batches 5160 and 5211 (Figure 7.11).

Overall, the accuracy of the classification model for the wet-primed cartridges was very impressive. It had a high accuracy and was further tested in the subsequent blind study (see Chapter 8).

Figure 7.13: Three of the Category 4c variants found within some wet-primed batches. Left: Category 4c-2. Centre: Category 4c-3. Right: Category 4c-4.

8 – BLIND STUDY

A blind study of selected cartridges bearing the sans-serif-ICI headstamp was performed to further test the accuracy of the classification models for the dry-primed and wet-primed cartridges. The classification function of LDA was used. It was unnecessary to allocate any of the collected data into a testing set for the blind study (because the data from the blind study cartridges was the testing set), therefore all of the collected data was used to train the model. Using all the data to build the classification model should produce more accurate predictions as all of the classes of data from the sampled cartridges were represented in the classification model.

8.1 CARTRIDGE SELECTION

There were 20 cartridges selected to be used in the blind study and cartridge selection was performed by Mr Kevan Walsh.

The first ten cartridges were selected randomly. This involved compiling a list of the batch numbers from all of the boxes of ammunition that were available. After this, a random number generator was used to randomly select ten boxes followed by randomised removal of one cartridge from each box of ammunition. An important point to note is that some of the cartridges selected using this method came from batches of ammunition that were not sampled in this project (see Table 8.1, "Not represented in model building"). This meant that it was possible that the classifiers for the headstamps on these cartridges were not represented in the data set used to build the model. Additionally, this removed the possibility of obtaining exactly correct predictions of batch (the classification model cannot predict a batch which it has not learnt).

The second set of ten cartridges was selected specifically by Mr Walsh. This set of cartridges included:

- Three cartridges originating from the same batch, two of which had been sampled in this project ("Replicates").
- A Tenex cartridge ("Tenex").
- A cartridge bearing a headstamp of English manufacture ("English").
- A cartridge bearing a significantly offset headstamp ("Offset").
- A cartridge with a copper case ("Copper").

- A rare variant headstamp (“Variant”).
- A cartridge produced just prior to the bullet changeover from Pattern 8 to Pattern 18/19 (“Bullet changeover”).
- A cartridge from a batch of Imperial brand ammunition (“Imperial”).

Each cartridge was removed from the box. Any identifying markings present on the cartridge were removed and a new identifier was marked on the cartridge. Each cartridge was presented for testing in a plastic bag with a sample number from 1 to 20. No other details (e.g. batch number) were available to the author prior to testing.

The selected cartridges with the relevant batch numbers, primed states and notes can be seen in Table 8.1.

Blind Study Cartridges			
Sample Number	**Batch Number**	**Primed State**	**Notes**
1	4372	Dry	Not represented in model building
2	4985	Dry	Not represented in model building
3	3922	Dry	Not represented in model building
4	4763	Dry	
5	4761	Dry	Not represented in model building
6	5010	Dry	
7	4843	Wet	Not represented in model building
8	4016	Dry	
9	4887	Dry	Not represented in model building
10	5135	Dry	
11	4763	Dry	Replicate
12	4847	Wet	English
13	4050	Wet	Tenex
14	4029	Dry	Bullet changeover, Not represented in model building
15	4763	Dry	Replicate
16	3970	Dry	Variant, Not represented in model building
17	4887	Dry	Offset
18	4847	Wet	Imperial, Not represented in model building
19	4567	Dry	Copper, Not represented in model building
20	4763	Dry	Replicate

Table 8.1: The cartridges selected for a blind study.

8.2 CLASSIFICATION USING LDA

Data was collected from the blind study cartridges as described in Chapter 4. After data collection, the coordinates were standardised and the relevant data transformations were calculated for classification by LDA. Of the 20 cartridges in the blind study, 16 were dry-primed and four were wet-primed. Consequently, the dry-primed cartridges were classified using the dry-primed analysis and the wet-primed cartridges were classified using the wet-primed analysis.

8.2.1 Dry-Primed Cartridges - Classification

Table 8.2 outlines the results of the predictions of the batch of origin for the dry-primed cartridges used in the blind-study.

Results for Dry-Primed Cartridges in Blind Study				
Sample Number	Batch Number	Predicted Batch	Distance from Actual Batch	True Distance from Actual Batch
1	4372*	4421	49	49
2	4985*	4411	574	230
3	3922*	3752	170	131
4	4763	4549	214	118
5	4761*	4661	100	45
6	5010	5024	14	13
8	4016	4079	63	51
9	4887*	4509	378	225
10	5135	5135	0	0
11	4763	4419	344	215
14	4029*	3965	64	41
15	4763	4593	170	92
16	3970*	3965	5	5
17	4887	4854	33	26
19	4567*	4500	67	59
20	4763	4763	0	0

Table 8.2: The results from the classifications of the dry-primed cartridges from the blind study. [* Not represented in model building].

The “Distance from Actual Batch” column contains the number of batches produced between the predicted batch and the true batch number for each (dry-primed) blind study cartridge. This was the same measure which used to assess the relative error of the predictions during cross validation of the data (see 7.1.3.3). Generally the predictions were close to the actual batch number (with two predictions that were exactly correct), however there were some predictions that were relatively far from the actual batch, namely for samples 2, 9 and 11. On average the prediction error for the 16 dry-primed blind study cartridges was 140 batches. This meant that, on average the predictions of the dry-primed cartridges from the blind study were 140 batches away from the actual batch of origin. Interestingly, this was approximately the same prediction error that was observed from the cross-validation of the data (see 7.1.3.3).

The column labelled "True Distance from Actual Batch" shows a more accurate assessment of the error of the predictions. The values in this column represent the distance between the predicted batch and the actual batch in terms of only the batches that were relevant to this project. To obtain these values, the CAC production records were used to exclude the irrelevant batches of cartridges (e.g. Short, Shot, copper, nickel and wet-primed cartridges). Therefore, this prediction error was regarded as being more accurate and relevant to this project. Analysis of the values contained within this column showed that the highest true prediction error observed was only 230 batches from the actual classification of the cartridge. On average the predictions were 81 batches from the actual batch. Furthermore, only five of the predictions were more than 100 batch numbers away from the true batch of the headstamp. This meant that approximately 69% of the predictions were less than 100 batch numbers from the actual batch of the cartridge. This shows that the predictions were very accurate when classifying the 16 unknown dry-primed cartridges from the blind study. Additionally, the true prediction error shown in this column demonstrates just how overstated the prediction errors were when the irrelevant batches were not taken into consideration.

Some interesting features were observed for some of the cartridges used in the blind study.

8.2.1.1 Sample 2

The headstamp of the cartridge which produced the highest prediction error (sample 2, batch 4985) was produced by a substantially worn bunter (Figure 8.1). There was an increased experimental error associated with image processing and data collection from headstamps that had been produced by worn bunters. This was due to uncertainties that arose as a result of the irregular edges. This could partly account for the high prediction error observed for this cartridge. Additionally, this batch number was not represented in the data used to train the classification model. It was possible that the classifiers for this "wear-variant" of the headstamps was not learnt by the LDA model. As a result of this, the classification model would have assessed the relative dimensions of the headstamp and classed it within the batch of best-fit which was 4411. Interestingly, batch 4411 contained another so-called "wear-variant" of headstamp which was similar, but not identical to that seen in the blind study cartridge (Figure 8.1). Taken together, these factors could have been responsible for the increased prediction error associated with sample 2 from the blind study.

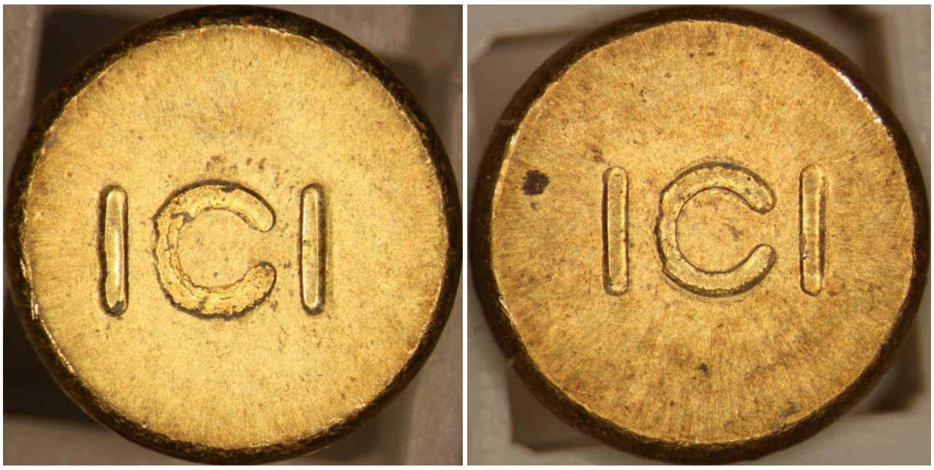


Figure 8.1: Photographs of the headstamps of two similar "wear-variants". Left: The headstamp from sample 2 of the blind-study. Right: The headstamp of a wear-variant which was sampled from batch 4411.

8.2.1.2 Sample 3

Sample 3 (from batch 3992) also had a relatively high prediction error and further analysis of the headstamp on this cartridge showed that it was also the result of a substantially worn bunter (Figure 8.2). Additionally, this batch number had not been represented in the data used to build the classification model. This could have been responsible for the relatively high prediction error seen for this cartridge.

Figure 8.2: Photograph of the headstamp from sample 3 in the blind study.

8.2.1.3 *Sample 9*

Another relatively high prediction error was recorded for sample 9 (from batch 4887). This batch was not represented in the data set used to build the model. The headstamp from this cartridge appeared to be a Category 4a headstamp. Batch 4887 was produced around the time that the headstamps were changed from Category 4a to Category 4b. Understandably, the batches produced around this time often contained mixes of Category 4a and 4b headstamps. This cartridge was predicted as coming from batch 4509 which falls into the middle of the time period when the Category 4a headstamps were used. This probably confirms that the cartridge had a Category 4a headstamp. However, the reason why this prediction error for this cartridge was relatively high cannot be explained. It could be from the relative similarities between the Category 4a headstamps. This would allow allocation of Category 4a headstamps into that general time period in which these headstamps were used, however it appears unlikely that a headstamp from this time period can be assigned more accurately. This can be shown in the graph of the posterior probabilities of batch membership for sample 9 (Figure 8.3). The posterior probabilities of batch membership are spread across a large range of batch numbers, each of which was produced during the period that the Category 4a headstamp was used.

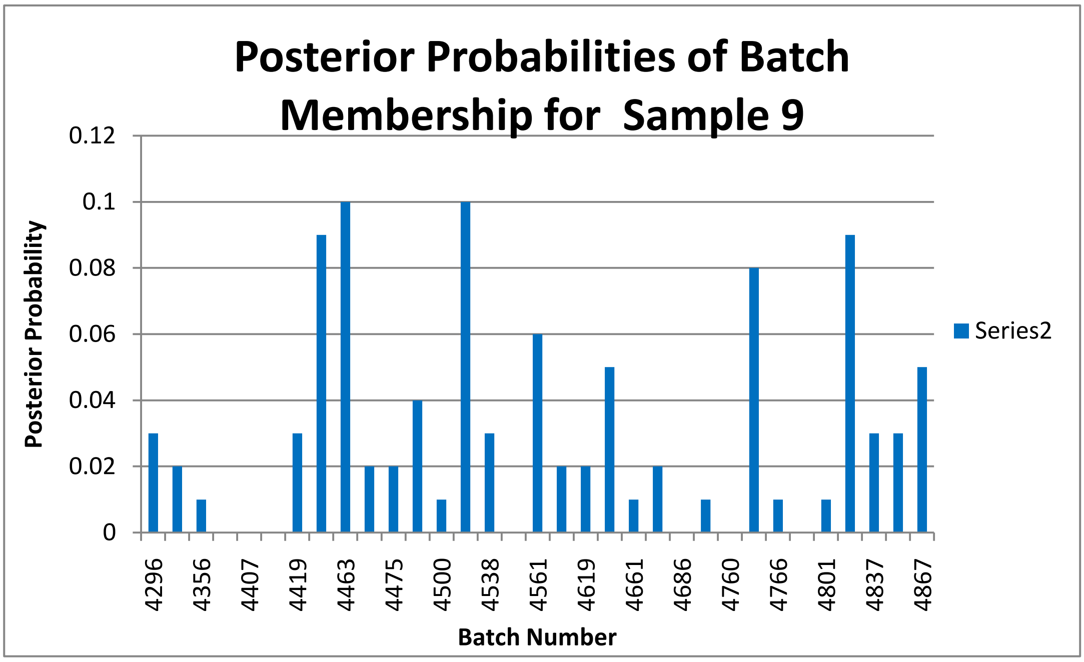


Figure 8.3: Graph showing the posterior probabilities of batch membership for sample 9 from the blind study.

8.2.1.4 Sample 16

The headstamp of sample 16 (from batch 3970) was a variant of the Wide-I headstamp as discussed in 7.1.1.4 and shown in Figure 7.3. Although this particular batch had not been sampled in this project, this headstamp was still able to be classified into the nearest batch that had been included in the data set used to build the classification model (batch 3965) which also included variant Wide-I headstamps. This shows that it was not explicitly necessary for each batch to be represented in the data set used to build the model, providing other batches within a close proximity had been sampled.

8.2.1.5 Sample 19

Within the dry-primed cartridges which were used in the blind study, there was one cartridge which had a copper case (sample 19, batch 4567). Cartridges with copper cases were not sampled in this project (these were considered as production that wasn’t directly relevant), however this cartridge was included in the blind study to see if the data from the headstamps from brass cartridge cases could be applied to those from copper cases. This cartridge was classified as having come from batch 4500. The relatively low prediction error (true prediction error of 59 batches) suggests that the data from the headstamps from brass cartridges can be applied to the headstamps from copper cartridges. This is perhaps not surprising, as it is likely that the same heading machines were used at ICI Australia to impress the headstamps on brass and copper cartridges. For this reason, one would expect the headstamps from the copper cartridges to follow the same patterns as those seen in the brass cartridges.

8.2.1.6 Samples 11, 15 and 20 (Replicates)

In the blind study there were three cartridges from batch 4763 (samples 11, 15 and 20). The headstamps of these three cartridges looked to be Category 4a. The box from which these cartridges were derived had been sampled in this project. Further, the cartridges labelled samples 11 and 20 had previously been sampled and were included in the data used to build the classification model. For this reason, samples 11 and 20 were true replicates. The prediction error for sample 11 was relatively high (true distance from batch was 215 batches). This was unexpected. The relatively high prediction error indicates that there has been significant experimental error associated with the data collected in this project. If there had been no experimental error, one would expect the data collected from the same headstamp on different occasions to be identical. If this had been the case, it would be expected that the predicted batch for sample 11 would have been exactly correct. As discussed for sample 9, the likely reason for the difference between the predicted batch and true batch could be due to the production of a large number of very similar Category 4a headstamps. Figure 8.4 shows a plot of the posterior probabilities of batch membership for sample 11 as calculated by the classification model.

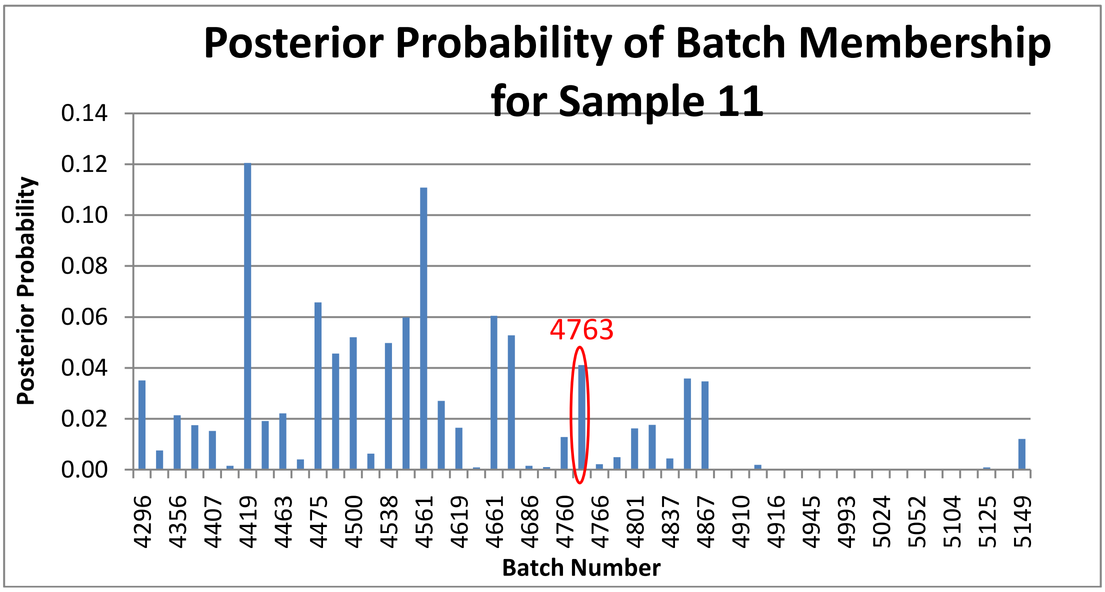


Figure 8.4: Graph showing the posterior probabilities of batch membership for sample 11 from the blind study.

The probabilities of batch membership for sample 11 (Figure 8.4) are split across many different batches (including the actual batch 4763) with varying strength of probability. This indicates that there are many similar headstamps distributed over a relatively large range. The period for which the posterior probabilities are high, broadly correlates to the period when the Category 4a headstamps were used. This corroborates the relative similarities between Category 4a headstamps as suggested previously.

The other cartridge which had been previously sampled (sample 20) from batch 4763, was able to be classified correctly in the blind study. The posterior probabilities of batch membership for sample 20 is shown in Figure 8.5. A similar pattern to what was seen for the posterior probability of batch membership for sample 11 was seen for sample 20, however for sample 20 a smaller range of batch numbers were represented in the predictions. Again, the period which is represented in the graph corresponds to when the Category 4a headstamp was used. This further corroborates the suggestion that the Category 4a headstamps produced over the relevant time period were very similar.

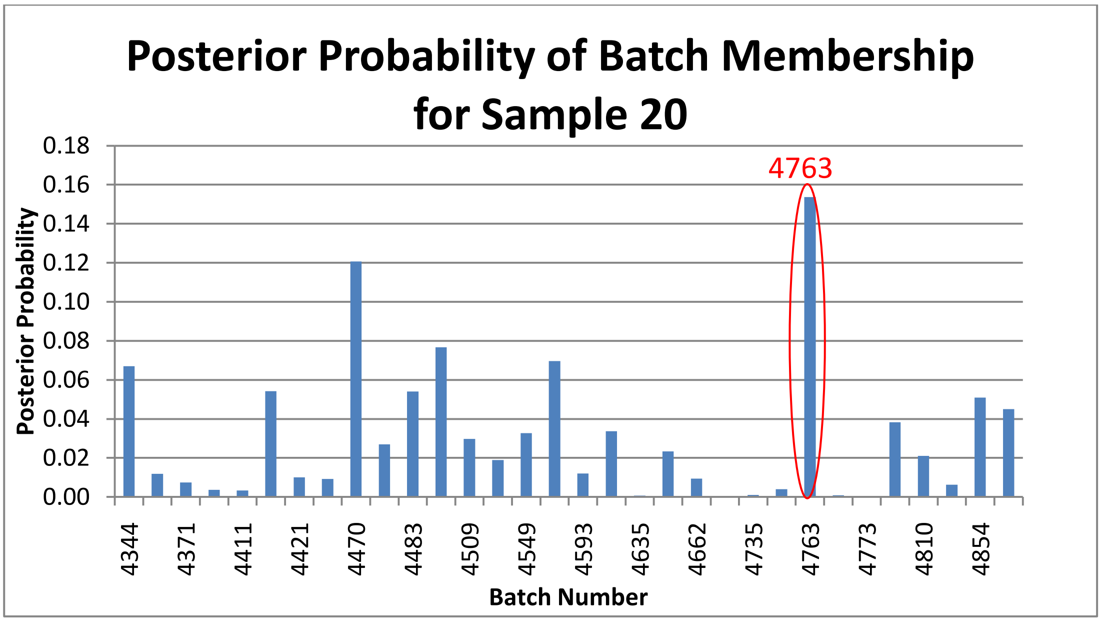


Figure 8.5: Graph showing the posterior probabilities of batch membership for sample 20 from the blind study.

The third cartridge from batch 4763 (sample 15) was not previously sampled in this project, however the patterns seen in the posterior probabilities of batch membership were similar to that seen for samples 11 and 20 (Figure 8.6). The true error for the prediction of the batch of this cartridge was 90 batches. This was slightly above the average error however the prediction was still relatively accurate.

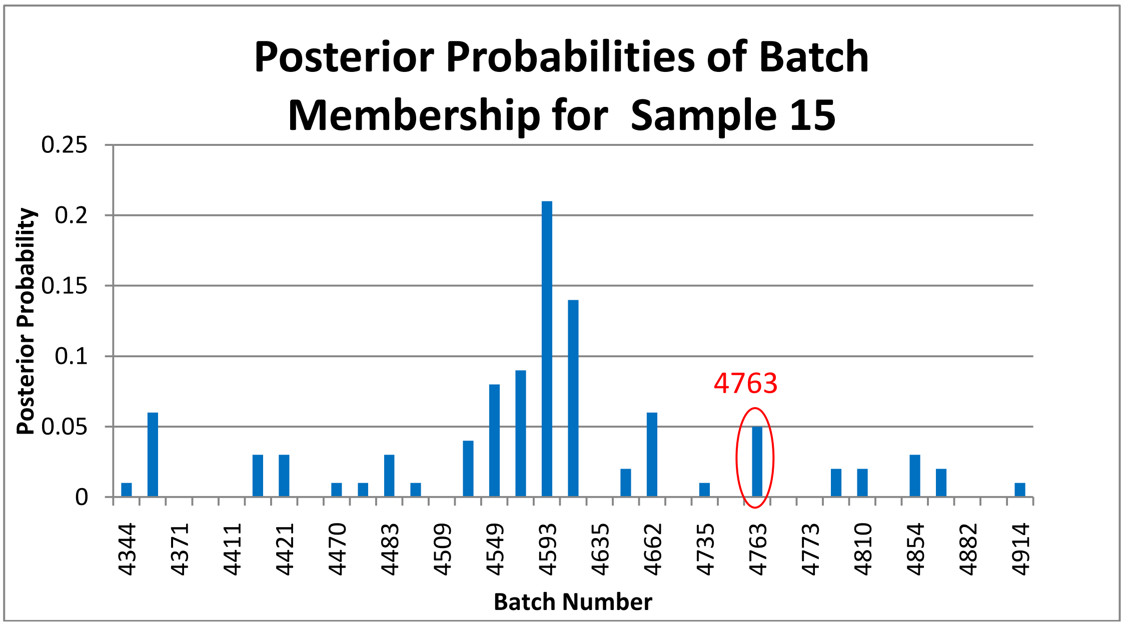


Figure 8.6: Graph showing the posterior probabilities of batch membership for sample 15 from the blind study.

8.2.2 Wet-Primed Cartridges - Classification

Table 8.3 outlines the results of the predictions of the batch of origin for the wet-primed cartridges used in the blind study.

Results for Wet-Primed Cartridges in Blind Study				
Sample Number	**Batch Number**	**Predicted Batch**	**Distance from Actual Batch**	**True Distance from Actual Batch**
7	4843	4922	79	11
12	4847	4846	1	1
13	4050	4050	0	0
18	4847	4848	1	1

Table 8.3: The results for the classifications of the wet-primed cartridges from the blind study.

The distance between the predicted batch and the actual batch for the sampled wet-primed cartridges were very low. The average prediction error (without eliminating any irrelevant batches) was 20 batches. Three of the four predictions were within one batch of the actual batch apart from sample 7 which was 79 batches away. When the prediction errors were considered in terms of only the relevant batches (i.e. only batches containing wet-primed brass cartridge cases) the distance between the predicted and true batch numbers for sample 7 was substantially reduced from 79 to 11 batches. This was not surprising as few wet-primed cartridges in brass cases were produced within the relevant time period of this project. The average distance between the predicted batch and the actual batch, when only considering the relevant batches, was approximately 3 batches. This showed that the classification model for the wet-primed cartridges was very accurate, although the success reflects to a large extent the low production numbers of wet-primed cartridges.

8.2.2.1 Samples 12 and 18

Samples 12 and 18 were from the same box of ammunition (batch 4847). This was an unusual batch of Imperial brand ammunition and this particular box had not been represented in the data set used to build the classification model (although a different box from batch 4847 had been used). The batch numbering on this box had been stamped with batch number 4839, but this had subsequently been crossed out, with batch 4847 also stamped onto this box. The CAC production records state that batch 4839 was Imperial brand, however this had been subsequently crossed and replaced with Long Rifle High Velocity brand. This probably explains the double batch numbering of this box and suggests that this batch was originally packed during batch 4839, however the batch number on the box was renumbered so that it fell within the batches where other Imperial brand ammunition was produced.

The headstamp on sample 12 was that produced by ICI Australia from the bunters of English manufacture. This was consistent with the Imperial brand of ammunition as these headstamps were seen almost exclusively in this brand. The predicted batch for this headstamp was 4846 which falls into the main period when the Imperial brand ammunition was produced (Imperial ammunition was mainly produced between batches 4845 to 4849 and 4919 to 4927). The headstamp on sample 18 differed to that on sample 12, even though these were from the same box of ammunition. The presence of mixed headstamps was common to the Imperial batches. The headstamp on sample 12 could be classed as Category 4c-1 which was previously identified as a variant of the Category 4c headstamps (see 7.2.3.3). Not surprisingly, the predicted batch for this headstamp was 4848, which also falls within the main period when the Imperial brand ammunition was produced.

8.2.2.2 Sample 7

Sample 7 was from a box of Long Rifle High Velocity brand ammunition (batch 4843). This batch was similar to batch 4847 (which samples 12 and 18 came from) as the CAC production record state that these batches were Imperial brand but were subsequently changed to Long Rifle High Velocity. Interestingly, batch 4843 was not loaded into an Imperial box as batch 4839 had been and the original batch numbering on the box had not been altered. The headstamps contained within the box from batch 4843 seemed to be similar to those contained within the Imperial batches, being made up of the headstamp of English manufacture and Category 4c-1 headstamps. Sample 7 was a Category 4c-1 headstamp. This headstamp was predicted as having come from batch 4922, another Imperial batch. This suggests that batch 4843 had been loaded with the same cartridges used in Imperial brand ammunition. The same probably applies to batches 4840 to 4844 which were also listed in the CAC production records originally as Imperial but then changed to Long Rifle High Velocity.

8.2.2.3 *Sample 13*

Sample 13 had a Tenex headstamp and was from batch 4050. Headstamps from batch 4050 had been sampled in this project however the headstamp from sample 13 had not been included in the data collection. The other Tenex batches sampled in this project included batches 4019, 4021, 4022 and 4049. Due to the obvious differences between the Tenex cartridges and the other wet-primed cartridges, it was not surprising that the batch prediction fell within one of the batches of Tenex cartridges. The predicted batch was exactly correct (4050) which could indicate that there are slight differences which exist between the Tenex headstamps seen in each Tenex batch. This is supported by the consideration of the posterior probabilities of batch membership (Figure 8.7). If all of the Tenex cartridges were indistinguishable, it would be expected that the posterior probabilities would be more closely and randomly distributed.

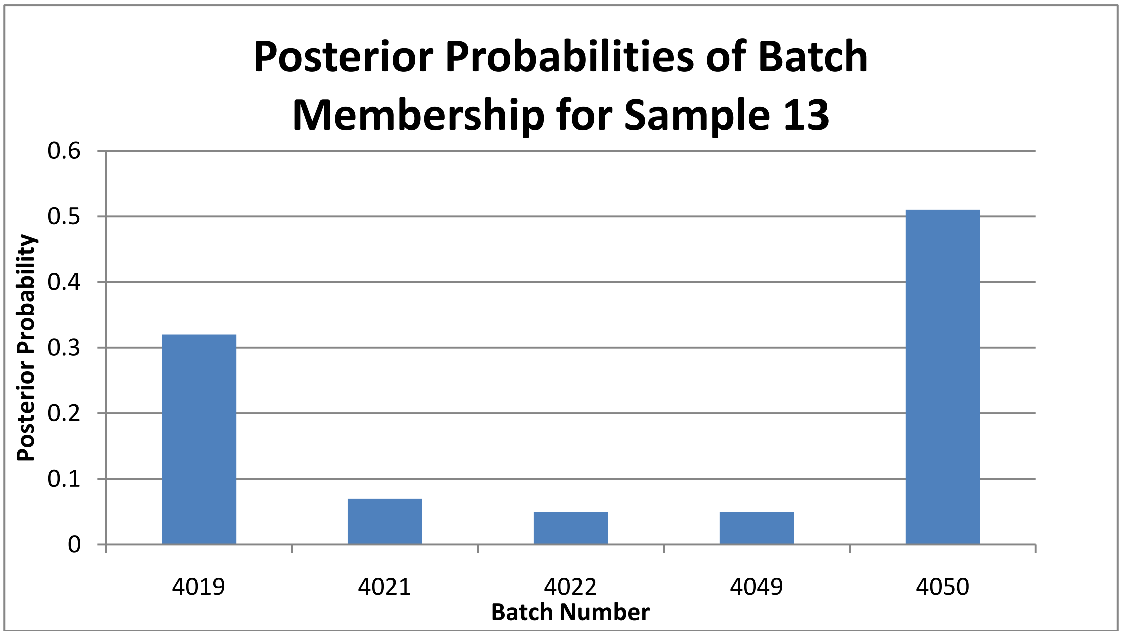


Figure 8.7: Graph showing the posterior probabilities of batch membership for sample 13 from the blind study.

9 – EXHIBIT 350

Although it was not the original intention this project, it was decided that exhibit 350 would be analysed using the statistical techniques used in this project. This could allow some determination of the time period this cartridge may have been produced which could allow some assessment of the probable type of bullet that was originally loaded into this cartridge.

9.1 COLLECTION OF DATA FROM EXHIBIT 350

Exhibit 350 was disposed of by the New Zealand Police on the Whitford tip on 27th July 1973 [2]. Therefore the cartridge was unavailable to be photographed in the same way as performed in the methodology of this project. However there was available, a series of black and white photographs of the headstamp of exhibit 350 that had been taken by the DSIR soon after its discovery. Some of these photographs were made available for this project. One of these photographs was selected to be used for data collection and this was subsequently converted into digital format by scanning the image (Hewlett Packard Scanjet 5400c) (Figure 9.1).

Figure 9.1: Scanned photograph of exhibit 350.

Once in digital format, the image was subject to the same data processing steps as outlined in the methodology of this project (see 4.7). The quality of the image was very good, however the lighting conditions for this photograph made defining the edges of the right “I” difficult. At the 1980 Royal Commission of Inquiry there was considerable discussion regarding the right “I” of exhibit 350. Mr McDonald believed that exhibit 350 had a right “I” which was unusually thick [2]. From the photograph of exhibit 350 it was difficult to define if the right edge of the right “I” was a true indentation from the headstamp or a surface effect on the cartridge. Defining the relative edges of the right “I” was important for how the image would be processed prior to data collection. In order to assess the headstamp, an enlarged image of the right “I” was examined (Figure 9.2).

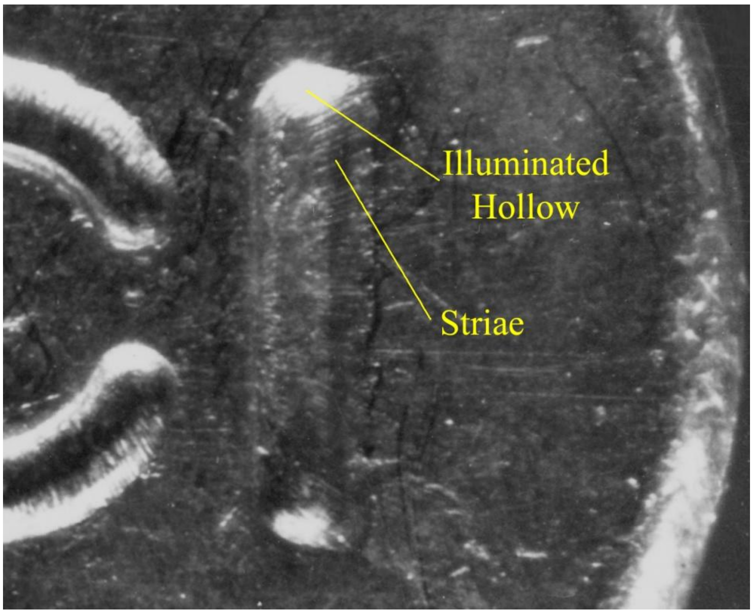


Figure 9.2: Image showing a close-up of the right “I” of exhibit 350.

Reflectivity at the top and bottom of the right “I” suggests that the head of the case was illuminated from the top and bottom. The top of the right “I” of exhibit 350 shows a large area where the light had been reflected (Figure 9.2). The reason why this area appears illuminated is probably due to a true indentation within the head of the cartridge. This suggests that the shape of the right “I” was unusually thick as Mr McDonald had postulated. This is further corroborated by the striae seen in the lettering which appears to run right out to the edge of the thick right “I”. For this reason, when the image of exhibit 350’s headstamp was processed, the right “I” was assumed to be thick as Mr McDonald had suggested. Figure 9.3 shows the resulting image after geometric processing.

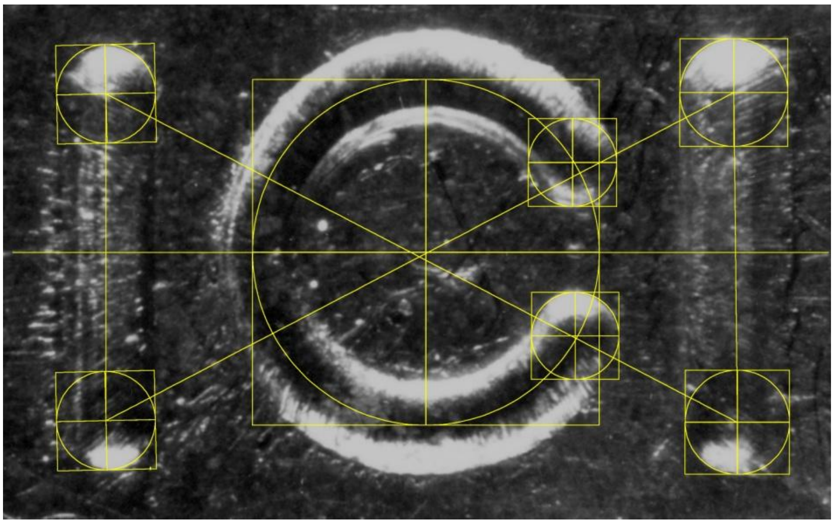


Figure 9.3: A close-up of the geometrically processed headstamp of exhibit 350.

Data was collected from the processed image of the headstamp in the same fashion as outlined in the methodology of this project (see 4.8). The original photographs did not include a scale. This made assessing the dimensions of the head of the exhibit 350 difficult. It was decided that the head dimensions (across the horizontal and vertical planes) from all the dry-primed cartridges sampled in this project would be averaged, with the averaged results used to scale exhibit 350. This was not seen as a major source of error as the dimensions of the heads of the cartridges across both planes were relatively consistent and were rarely more than 0.05mm from the average measurements.

After the data was collected, it was subject to the same data standardisation and transformation as performed in the methodology of this project (see 4.9).

At the 1980 Royal Commission of Inquiry [2], it was generally agreed that exhibit 350 was primed using the dry-priming technique. The appearance of the rim from the photographs supported this finding. Therefore the data collected from exhibit 350 was used in the dry-primed analysis.

9.2 Assessment of Exhibit 350's Placement within the PCA Biplot

Prior to classification using LDA, the data from exhibit 350 was added to the rest of the dry-primed data and a PCA biplot was produced (Figure 9.4). The data point corresponding to exhibit 350 is shown in red.

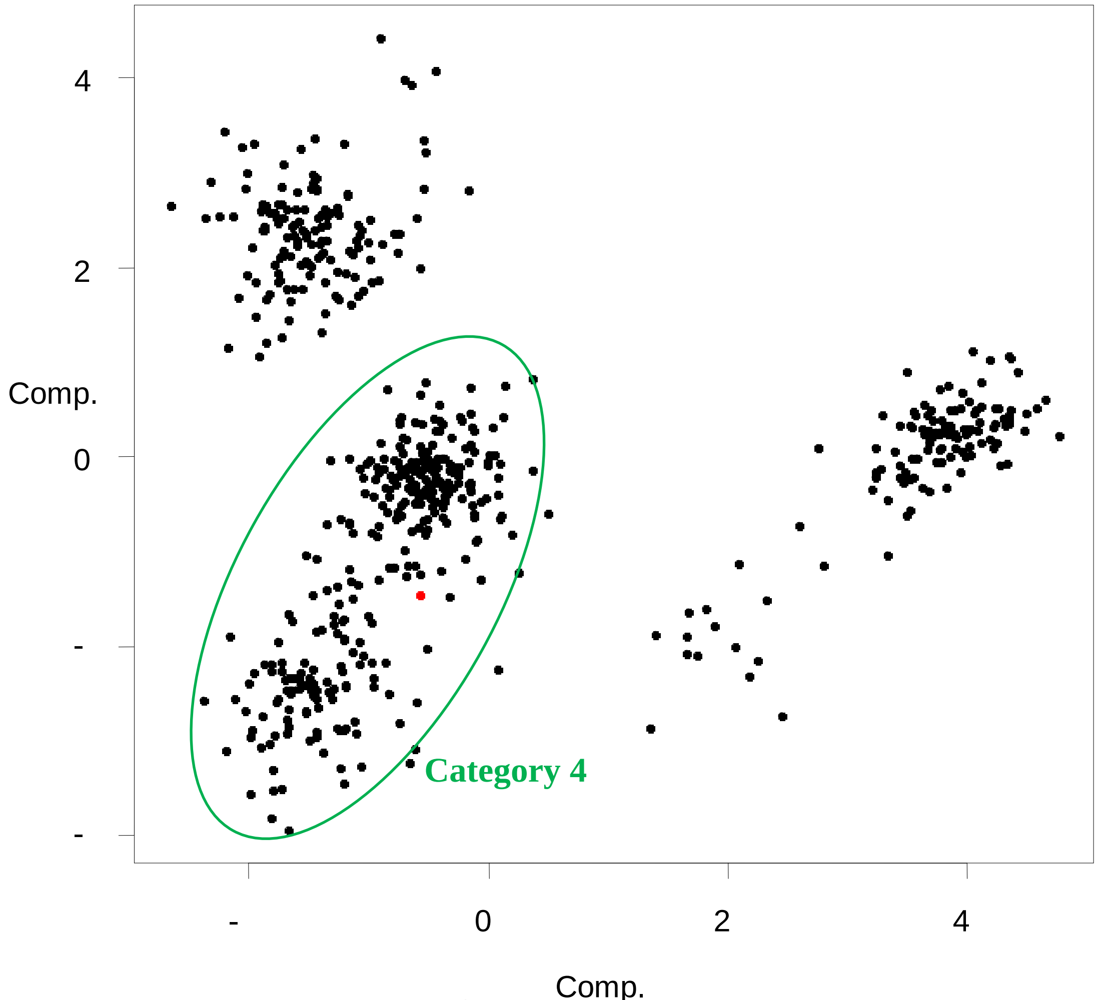


Figure 9.4: Principal components biplot for the dry-primed cartridges and exhibit 350. The data point relating to exhibit 350 is shown in red.

In Figure 9.4 the group corresponding to the Category 4 headstamps has been outlined. From analysis of the bullet-type distribution within the dry-primed cartridges (Figure 7.4) it should be noted that none of the Category 4 headstamps which were sampled in this project were loaded with Pattern 8 bullets. Within the group of Category 4 headstamps there were two main sub-groups. The first of these lies at the top of the group and this corresponds to the Category 4a headstamps. The second of these contains the Category 4b headstamps and this lies below the Category 4a group and is less tightly packed. The data point corresponding to exhibit 350 lies below the Category 4a grouping which suggests that exhibit 350 bears a headstamp of the Category 4b variety. The Category 4b headstamps appeared to have been used after batch 4882 (produced after September 1967). This was around four years after the cessation of the Pattern 8 bullets.

Taken together, these findings strongly suggest that exhibit 350 would not have been loaded with a Pattern 8 bullet.

9.3 CLASSIFICATION OF EXHIBIT 350 USING LDA

The same classification model that had been used previously to classify the cartridges in the blind study was used to classify exhibit 350.

Exhibit 350 was predicted as having come from batch 4916 (packed 13th May 1968).

The low prediction error of the classification model, which was ascertained during cross-validation of the data and in the blind study (see 7.1.3.3 and 8.2.1), suggests that exhibit 350 was likely to have been produced either in this very batch or in another batch produced around the same time period.

The prediction for exhibit 350 (batch 4916) fell within the time period in which the Category 4b headstamps were used which provided further evidence that this headstamp was of the Category 4b variety. Additionally, the predicted batch was produced long after the changeover from Pattern 8 to Pattern 18 and 19 bullets which further suggests that exhibit 350 would not have been loaded with a Pattern 8 bullet.

The posterior probabilities of batch membership for the classification of exhibit 350 are shown in Figure 9.5.

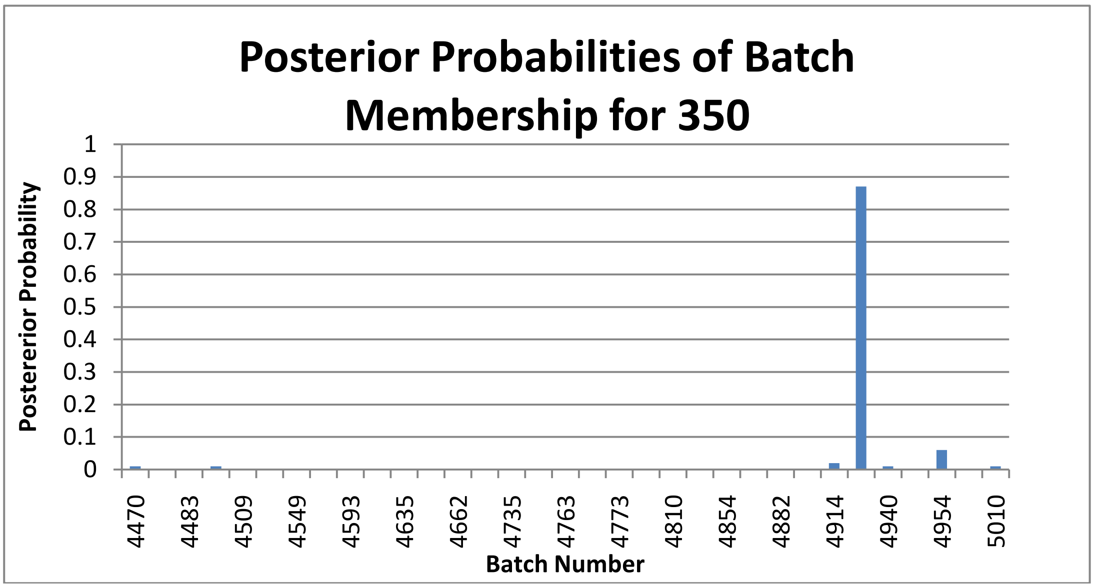


Figure 9.5: Graph showing the posterior probabilities of batch membership for exhibit 350.

Figure 9.5 shows an overwhelming posterior probability (87%) that exhibit 350 originated from batch 4916. Obtaining a posterior probability of batch membership as high as this by chance would be extremely unlikely. This could suggest that the unusually thick right “I” of exhibit 350 was genuine, making this headstamp an unusual wear-variant. As bunters become worn, the raised lettering becomes slightly thicker and fatter due to the repeated impact of the bunter on the cartridge cases [37]. For this reason, it is plausible that the thick right “I” of exhibit 350 could have arisen from bunter wear [2]. During this project, genuine wear-variants of headstamps were rarely encountered and when they were encountered they were seen in limited numbers. An example of this is the Wide-I variant of headstamp (Figure 7.3). It is possible that exhibit 350 was a wear-variant of the Category 4b headstamp. Further, it is possible that the same wear-variant was found in the sampled cartridges from batch 4916. This could have resulted in the high posterior probability of batch membership. Analysis of the headstamps on the cartridges found with the boxes from batch 4916 (there are two boxes that have been obtained from this batch) showed that headstamps with a relatively thick right “I” were common to this batch. However, comparison of the headstamps found in batch 4916 to the headstamp found on exhibit 350 was difficult due to the substantial differences with how the photographs were captured, particularly with regard to lighting. If exhibit 350 had been available, it would have been useful to re-capture the images of this headstamp using the same photography techniques utilised in this project. From here, comparison of the headstamps could be performed. Where the headstamps were found to be very similar, the examination of microscopic detail could allow determination of whether the same bunter had been used to produce the headstamps. This could have provided strong evidence that exhibit 350 originated from batch 4916, or a similar batch where the same bunter was in use (NB: Mr Cook claimed that each bunter had a life of around six to ten days which broadly correlates to six to ten batches).

Interestingly, the posterior probabilities of exhibit 350 originating from a batch produced before 4470 were zero. This suggests that there were no significant similarities between exhibit 350 and the headstamps on the cartridges produced prior to batch 4470 (packed 12th June 1965).

9.4 CONCLUSION

The principal components analysis and classification of exhibit 350 using LDA both suggest that exhibit 350 was produced long after the cessation of the use of Pattern 8 bullets. It is therefore unlikely that this cartridge case was loaded with a Pattern 8 bullet. The unusually high posterior probability of batch membership for exhibit 350 originating from batch 4916 suggests that exhibit 350 was a wear variant which was very similar (if not identical) to the headstamps found in batch 4916.

10 – REFINING THE CLASSIFICATION MODEL

As a refinement to the LDA classification model for the dry-primed cartridges, it was decided to split the batches into several blocks of data, with each block corresponding to a particular headstamp design. Therefore, rather than trying to classify an unknown cartridge to a particular batch, this approach should classify the cartridge to a general category of headstamp design.

It was feasible to produce a block analysis of the dry-primed data because the headstamp variants appeared to occur sequentially over time. However, the headstamp variants in the wet-primed cartridges did not follow a sequential pattern, particularly with regard to the Category 4c variants of headstamp. The Category 4c variants (mainly 4c-2, 4c-3 and 4c-4) were not seen sequentially, instead these were seen together in a large number of batches. For this reason, it was determined that a block analysis of the wet-primed data would not be appropriate.

10.1 DEFINING THE BLOCKS OF DATA

The relevant batches containing the various categories of headstamp had to be defined. Ideally, this would be performed using information from outside the observations seen in the data collected for this project. The ICI Australia production records would have been an invaluable external resource to determine when the headstamp design changes took place, however these are no longer in existence. During the prosecution of Mr Thomas and the subsequent 1980 Royal Commission of Inquiry there were many different individuals who gave evidence regarding when the headstamp design changes took place. However, these were broad estimates and there were substantial discrepancies between the dates given by different individuals. This is perhaps not surprising due to the time interval between the actual design changes taking place at the ICI Australia factory and when the evidence was given. The dates stated by various individuals were seen to be too inaccurate and therefore these were not deemed appropriate for use in this project.

Instead, it was considered necessary to define when the relevant headstamp changes took place from what was seen for the collected data.

Within the headstamps on dry-primed cartridges there were four main variants of headstamps (Category 3, Wide-I, Category 4a and Category 4b). Therefore the data was split into these four separate blocks of data.

From analysis of the data the following observations were made (with dates assigned using the CAC production records):

- Category 3 headstamps were mainly seen between batches 3410 and 3963 (11 August 1960 to 14 May 1963);
- Wide-I headstamps between batches 3965 and 4278 (15 May 1963 to 3 September 1964);
- Category 4a headstamps between batches 4296 and 4867 (22 September 1964 to 18 August 1967); and
- Category 4b headstamps between batches 4882 and 5135 (19 September 1967 to 23 June 1970).

These batches were relatively consistent with the evidence given by various individuals during the judicial proceedings of the Crewe murders and the 1980 Royal Commission of Inquiry.

10.2 CROSS-VALIDATION OF THE BLOCK DATA

A cross-validation method was used to assess the accuracy of the block predictions. Similar to what was done in the statistical analyses previously, a modified version of the hold-out method was used. The data from the dry-primed headstamps were grouped into the relevant blocks as described above, then approximately two-thirds of the observations contained within each block were allocated into the training set. The remaining data from each block was allocated into the testing set. The training set was used to build the classification model. Once the classification model was built, the testing set was introduced to the model as unknown data and the classification model was used to predict the most likely block of origin.

10.2.1 Assessing the Accuracy of the Block Classifications

A prediction table from cross-validation of the block data is shown in Table 10.1. Although the prediction tables are subject to change from analysis to analysis (due to the random assignment of the training set and testing set) this table was typical of the results.

		Testing Set			
		Block 1	Block 2	Block 3	Block 4
Predicted Block	Block 1	46	1	0	0
	Block 2	2	40	1	0
	Block 3	0	1	63	0
	Block 4	0	0	2	36

Table 10.1: A prediction table from cross-validation of the block data.

For information regarding the interpretation of these tables see 7.1.3.2.

The prediction table (Table 10.1) shows that the block predictions were very accurate with the vast majority of the predictions lying in the diagonal of the table.

The cross-validation of the data was repeated 200 times with the number of correct predictions recorded in each analysis. In each cross-validation analysis, 381 observations were used to train the model and 192 observations were used for block predictions. On average, 94.2% (std-dev = 1.4) of the predictions were classified into the correct block. This shows that the classification model for the block predictions was very accurate. It was expected that there would be some incorrect predictions in each analysis due to the presence of boxes containing mixed headstamps. Obviously, cartridges from a batch containing Wide-I headstamps mixed with Category 4a headstamps would produce some incorrect predictions as one would expect the Wide-I headstamps to be predicted as having come from block 2, and the Category 4a headstamps as having come from block 3. Batches containing mixed headstamps were more prominent around the fringes of the various blocks. This is perhaps not surprising as during the changeover of headstamp designs there would have been batches of cartridges produced which contained mixes of the relevant headstamps, as the old bunters were gradually replaced with bunters of the new design. There were also a number of batches sampled that contained mixed headstamps due to the probable addition of cartridges of impure provenance. However, the high accuracy of the block prediction shows that the mixed batches were not a significant problem.

Various prediction tables from the cross-validation of the data were examined and some interesting features were observed. Where the predictions were wrong, they were always classified into one of the neighbouring blocks. For instance, a prediction for block 3 (Category 4a) would be: correctly classified (block 3); classified into block 2 (Wide-I); or classified into block 4 (Category 4b). Additionally, the wrong predictions generally occurred from the batches of cartridges that were produced around the time of the changeover of the headstamp designs as discussed above.

10.2.2 Classification of Exhibit 350 using the Block Analysis

The block analysis was used to classify exhibit 350 into one of the blocks.

Exhibit 350 was classified as having come from block 4 (Category 4b). The posterior probability of the block prediction of exhibit 350 is shown in Figure 10.1. The posterior probability for classing exhibit 350 into block 4 was 100%. This shows that the headstamp on exhibit 350 was almost certainly Category 4b.

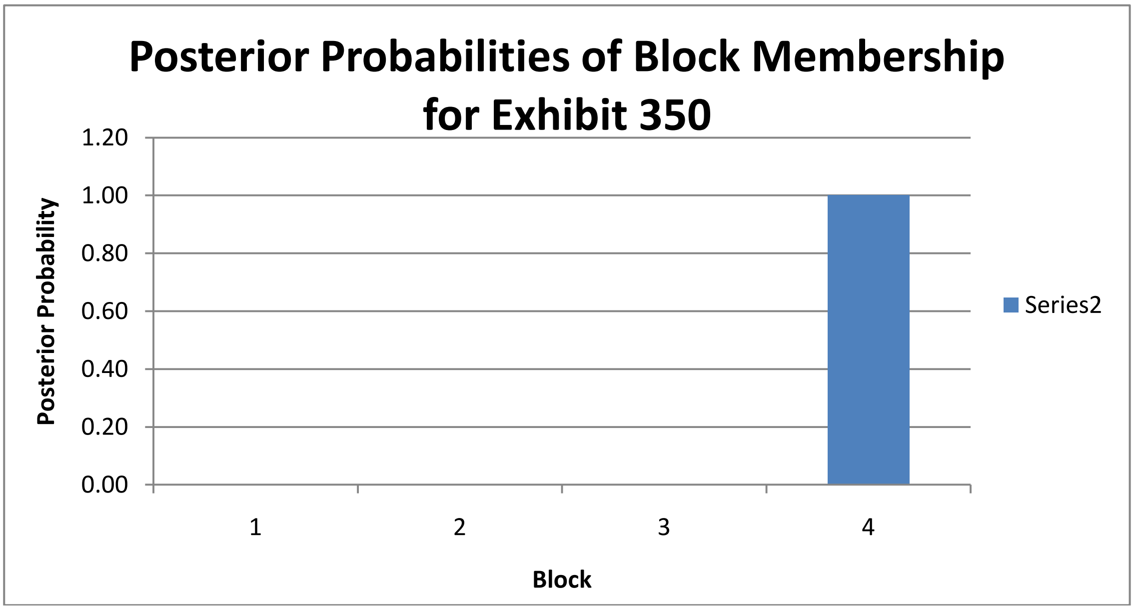


Figure 10.1: Graph showing the posterior probabilities of block membership for exhibit 350.

10.3 CONCLUSION OF BLOCK ANALYSIS

The block analysis proved very accurate for broad predictions of production period for unknown cartridges. The relative accuracy of this classification method makes this very useful. However, it is important to understand that this classification model only groups cartridges based on large differences between headstamp designs. It was not as specific as the classification model used in the main statistical analysis and in the blind study (see Chapter 7 and Chapter 8) because it does not look to identify small differences between very similar headstamps. Additionally, as the headstamps have only been classed into four categories there are numerous wear variants that were not represented as separate classes of headstamp.

The block analysis classes the headstamps into four separate headstamp categories, each of which was used for varying time periods. The predictions of the block in which the headstamp belongs was only as accurate as the time period in which the appropriate headstamp was used. From analysis of the data collected in this project, Category 3, Wide-I, Category 4a and Category 4b headstamps appeared to have been used for approximately 33 months, 16 months, 35 months and 33 months respectively.

Although the block predictions for time of production were quite broad (ranging from within a 35 month period to within a 16 month period) they were still very useful. For instance, the prediction of exhibit 350 coming from block 4 was very strong evidence that this cartridge had a Category 4b headstamp. This was useful as it shows that this cartridge was probably produced between batches 4882 and 5135 (between 19 September 1967 and 23 June 1970). If an analysis such as this had been available during the 1980 Royal Commission of Inquiry it could have been used to provide strong evidence that this cartridge was produced long after the cessation of Pattern 8 bullets.

11 – SUMMARY OF FINDINGS AND LIMITATIONS

This project set out to perform a large scale analysis of the sans-serif-ICI headstamp in order to investigate whether or not subtle changes in the class characteristics of the headstamps produced by CAC between 1960 and 1971 could be discerned to gain an accurate picture of when the changes took place. This could subsequently be used for the prediction of the period of manufacture of an unknown cartridge case.

The block analysis of the data (see Chapter 10) showed that the four main class-variants of the dry-primed headstamps (Category 3, Wide-I, Category 4a and 4b) were able to be discerned with high accuracy. This analysis was able to determine, with 94.2% accuracy, the relative time block within which an unknown cartridge was produced. These predictions of time period of manufacture were quite broad, however this analysis did show that the major variants of the headstamps on dry-primed cartridges were able to be readily discerned.

More accurate predictions of cartridge production date were able to be obtained using the LDA classification model for the wet-primed and dry-primed cartridges (see Chapter 7). These were predictions of a specific batch of origin. However, a study of the posterior probabilities of batch membership for all batches tested allowed an assessment of the likely range of possible batches of origin. This model not only looked for the differences between the main categories of headstamp (Category 3, Wide-I, 4a and 4b) but also the differences seen within the various categories of headstamp.

The model for classifying the dry-primed cartridges had an average error of approximately 138 batches, as determined from cross-validation of the data (see 7.1.3.3). This meant that the predicted batch was, on average, 138 batches from the true batch of the cartridge. However, this prediction error was overstated due to the inclusion of irrelevant production batches. One hundred and thirty eight batches corresponds to a production period of approximately five to six months. This shows that the classification model was able to classify the unknown cartridges into a relatively narrow production period. For the blind study the average prediction error for the classification model was 140 batches (see 8.2.1). Further analysis of the predictions showed that the true error of the classification model was only 81 batches, when only the relevant batches of ammunition were considered.

The model for classifying the wet-primed cartridges had an error of about 46 batches, as determined from cross-validation of the data (see 7.2.3.3). Forty six batches corresponds to a production period of approximately two months. This shows that the classification model for the wet-primed model was very accurate at classifying the data into a very specific production period. For the blind study the average prediction error of the classification model was 20 (see 8.2.2). Further analysis of the predictions showed that the true error of the classification model for the blind study was three batches when only the relevant batches of ammunition were considered. However, although the prediction error for the wet-primed cartridges was very low, this was assisted by the small numbers of batches of wet-primed cartridges used by CAC and therefore the relative rarity of wet-primed batches of cartridges.

This project was very successful in developing a method for accurate predictions of production period for cartridges of unknown origin.

When the dry-primed classification model was applied to the cartridge case found at the crime scene of the Crewe murders (exhibit 350), this cartridge case was predicted as having originated from batch 4916 (packed 13th May 1968). This was further supported by the block prediction obtained from the refined classification model which suggested exhibit 350 was produced between batches 4882 (packed 19 September 1967) and 5135 (packed 23 June 1970). Taken together, this strongly supports the proposition that exhibit 350 was produced long after the cessation of the production of Pattern 8 bullets (last loaded at CAC on the 8th of November 1963). Therefore the analysis of exhibit 350 supports the view held by Dr Sprott and the findings of the 1980 Royal Commission of Inquiry, that this cartridge case could not have been loaded with a Pattern 8 bullet.

11.1 LIMITATIONS OF THIS STUDY

There were limitations associated with this study. Experimental error is unavoidable in any study and it is important that precautions are taken in order to try to minimise this error. The main areas of this project which were vulnerable to experimental error included the geometric processing of the images and subsequent data collection. Geometric processing was particularly vulnerable to experimental error due to the subjective nature of fitting the shapes to the various features of the headstamps. Precautions were taken to avoid as much error as possible by developing a set of rules to consistently deal with the processing of the images, particularly with regard to the headstamps where the edges of the lettering were hard to define. Evidence of some experimental error was seen in the classification of sample 11 during the blind study (see 8.2.1.6). This particular headstamp had been previously sampled and was used in the data set used to build the classification model. However, when the data was recollected from this headstamp (as an unknown cartridge in the blind study) and used for classification, the model failed to correctly classify the cartridge into the correct batch of origin. This suggested that there were some discrepancies between the data that was originally collected and the data collected during the blind study. Although experimental error was inevitable, the relative accuracy of the final classification model suggests that this was not a problem within this project.

The other major limitation arose from the uncertainty of the provenance of cartridges used in the survey. The boxes of ammunition used for sampling in this project were 40 to 50 years old. For this reason, the presence of cartridges of impure provenance within some of the sampled boxes was basically unavoidable. Stringent measures were taken during the selection of boxes for sampling to try and remove the boxes containing obvious non-genuine mixes of headstamps. However, it was acknowledged that there were batches of cartridges produced during various time periods (e.g. during the changeover of a headstamp design) which contained genuine mixes of headstamps. It was accepted early on in this project that boxes containing cartridges of likely impure provenance would be sampled and therefore this was taken into consideration when assessing the results from this project. The boxes that were sampled which contained cartridges of impure provenance, or suspected impure provenance, appeared to result in increased prediction errors during cross-validation of the data. This was true for both the wet-primed and dry-primed analysis. An example of some cartridges of suspected impure provenance from batch 4766 can be seen in Figure 7.10 (column A on the graph) where the prediction error was substantially high (see 7.2.3.3).

There was also potential for cartridges of impure provenance to produce increased prediction errors during the blind study. It was possible that some of the cartridges selected to be used in the blind study were of impure provenance. Understandably, this means that the batch from which these cartridges came (which was used to assess the accuracy of the predictions) would not be representative of the true (original) batch of the cartridge leading to increased prediction errors.

Although the sampling of cartridges of impure provenance was inevitable, they did not appear to substantially impact the accuracy of the classification models for the wet-primed and dry-primed cartridges.

APPENDIX I

A timeline was constructed to establish the order of events of the Crewe murders and subsequent prosecution.

The dates and events have been principally compiled from "Report of the Royal Commission to Inquire into the Circumstances of the Convictions of Arthur Allan Thomas for the Murders of David Harvey Crewe and Jeanette Lenore Crewe" [2].

17th June 1970: The last sighting of Mr David Harvey Crewe and Mrs Jeanette Lenore Crewe as they drove home from a stock sale in Bombay. On the evening of this date, three rifle shots were heard by Mr and Mrs Priest (neighbours of the Crewe's) coming from the direction of the Crewe farm [1].

22nd June 1970: A bloodied crime scene was discovered at the Crewe household by Len Demler (Mrs Crewe's father). Mr and Mrs Crewe were absent, however from the bloodied state of the house it was assumed both had been killed. The Crewe's 18-month old daughter was found inside the house, alive but obviously distressed. The initial search of the house for evidence yielded no clues as to how Mr and Mrs Crewe were killed.

16th August 1970: Mrs Crewe's body was found in the Waikato River at a place known as "Devil's Elbow". Mrs Crewe had received a gunshot to the head. Fragments of a .22LR calibre projectile were recovered from her head. Later, another unsuccessful search of the house and surrounding area was performed with special attention paid to finding a fired cartridge case.

17th August 1970: Rifles gathered from relatives and associates of Mr and Mrs Crewe and from residents within a five mile radius of the house.

19th August 1970: Preliminary findings by DSIR show that neither Mr Arthur Allan Thomas's rifle nor the Eyre family rifle can be excluded as having fired the fatal bullet recovered from Mrs Crewe.

16th September 1970: Mr Crewe's body was found in the Waikato river, upstream from where Mrs Crewe's body had been recovered. Along with Mr Crewe's body, a car axle is recovered which had been used to weigh the body down.

19th September 1970 (approximately): The bullet fragments recovered from Mr Crewe were compared with the rifling characteristics of the gathered rifles. Although the bullet was severely damaged, preliminary findings by DSIR scientists showed that neither the Thomas rifle nor the Eyre family rifle could be excluded as having fired the fatal bullet.

13th October 1970: Detective Johnson collects an uncounted box of .22LR ammunition from Mr Thomas's farm. Later that day, the police perform a reconstruction of how Mr and Mrs Crewe could have been murdered.

Between 30th September – 27th October 1970: Mr and Mrs Priest recalled hearing two shots fired from the direction of the Crewe farm. It was possible that this was during the Police reconstruction.

13th-16th October 1970: Scientists at DSIR confirm preliminary findings that neither the Thomas rifle nor the Eyre rifle could be excluded as having fired the fatal bullets.

27th October 1970: Detective Sergeant Charles and Detective Sergeant Parkes were sent to the Crewe farm to search an area of garden beside the fence outside the back door of the house. The reasoning behind this search was that if the murders had been performed in the manner outlined in the Police reconstruction, a fired cartridge case could have been ejected into the garden. Within two hours of beginning the search, a fired .22 cartridge case was found. It was later alleged that this area had been searched twice before. This fired cartridge case later became "exhibit 350" and was one of the major pieces of evidence used in the subsequent prosecution.

9th November 1970: The firing pin impression on exhibit 350 was compared, by scientists at DSIR, to that of the collected rifles. The findings concluded that only Mr Thomas's rifle (and no other) could have fired exhibit 350.

11th November 1970: Mr Thomas was arrested and charged with the murders of Mr and Mrs Crewe.

15th February – 2nd March 1971: The first trial of Mr Thomas for the murders of Mr and Mrs Crewe takes place. The jury found Mr Thomas guilty of murder on both counts. Mr Thomas was sentenced to life imprisonment.

6th May 1971: Appeal to the conviction of Mr Thomas was lodged in the Court of Appeal.

18th June 1971: Appeal was dismissed.

Late 1971: Petition submitted to the Governor General, pursuant to Section 406 of the Crimes Act 1961, seeking a re-trial of Mr Thomas.

2nd February 1972: Sir George McGregor (a retired Judge of the Supreme Court) states that in his view there has been no miscarriage of justice with regard to the imprisonment of Mr Thomas.

2nd June 1972: A further petition was lodged in the Court of Appeal (known as the "first referral").

5th-6th February 1973: The evidence for the first referral was heard before the Court of Appeal.

26th February 1973: Court of Appeal orders a second trial of Mr Thomas for the murders of Mr and Mrs Crewe.

26th March – 16th April 1973: The second trial of Mr Thomas for the murders of Mr and Mrs Crewe takes place. The jury finds Mr Thomas guilty of murder on both counts and he was again sentenced to life imprisonment. Towards the end of the second trial (10th April 1973) Dr Sprott received a letter and some cartridges from Mr J. B. Ritchie. The letter informs Dr Sprott of the different types of headstamps and their relationship to bullet type. Dr Sprott begins his study of the various categories of headstamps.

12th June 1973: Appeal lodged to the Court of Appeal regarding the second conviction of Mr Thomas.

11th July 1973: Appeal was dismissed. A further petition was lodged to the Governor General by Dr Thomas Sprott and Mr Pat Booth.

27th July 1973: Exhibit 350 was destroyed, along with other evidence relating the Crewe murders.

Between 27th July 1973 - 9th December 1974: The convictions of Mr Thomas were referred to the Court of Appeal (second referral). The main issue addressed was whether exhibit 350 could have been linked to the fatal bullets.

9th December 1974 – 8th January 1975: The second referral to the Court of Appeal takes place.

29th January 1975: Five Judges and the Court of Appeal give a unanimous judgement that it had not been sufficiently proven that exhibit 350 could not have contained either of the fatal bullets.

Between 29th January 1975 and 4th July 1978: Appeal lodged to the Privy Council regarding the judgement from the second referral to the Court of Appeal.

4th July 1978: The Privy Council advises that they have no jurisdiction to entertain such an appeal.

1978: Mr David Yallop publishes a book "Beyond Reasonable Doubt" which reviews the case against Mr Thomas. The book states that a miscarriage of justice has occurred.

October 1978: As a result of the allegations that Mr Thomas was a victim of a miscarriage of justice, the Prime Minister of New Zealand (the Right Honourable Sir Robert Muldoon) appoints Mr Adams-Smith, QC, to review the convictions and report to him.

16th January 1979: Mr Adams-Smith delivers his first report to the Prime Minister.

Early December 1979: Mr Adams-Smith delivers his second report to the Prime Minister.

17th December 1979: As a direct result of Mr Adams-Smith's second report to the Prime Minister, Mr Thomas is granted a free pardon for the murders of Mr and Mrs Crewe. The pardon was granted pursuant to Section 407 of the Crimes Act 1961. Mr Thomas was paid $950,000 in compensation as a result of the miscarriage of justice that occurred. The free pardon that was given to Mr Thomas meant that he could never be re-trialled for the murders of Mr and Mrs Crewe.

1980: A Royal Commission of Inquiry is carried out to investigate the circumstances and convictions of Mr Thomas. The evidence from the Royal Commission suggested that Detective Hutton and Detective Johnson had planted evidence (exhibit 350) at the crime scene. However, neither officer was ever prosecuted due to lack of evidence to justify a prosecution.

2010: In response to a request from Rochelle Crewe (daughter of Mr and Mrs Crewe) the Police began an assessment and review of the Police homicide investigation into the Crewe murders.

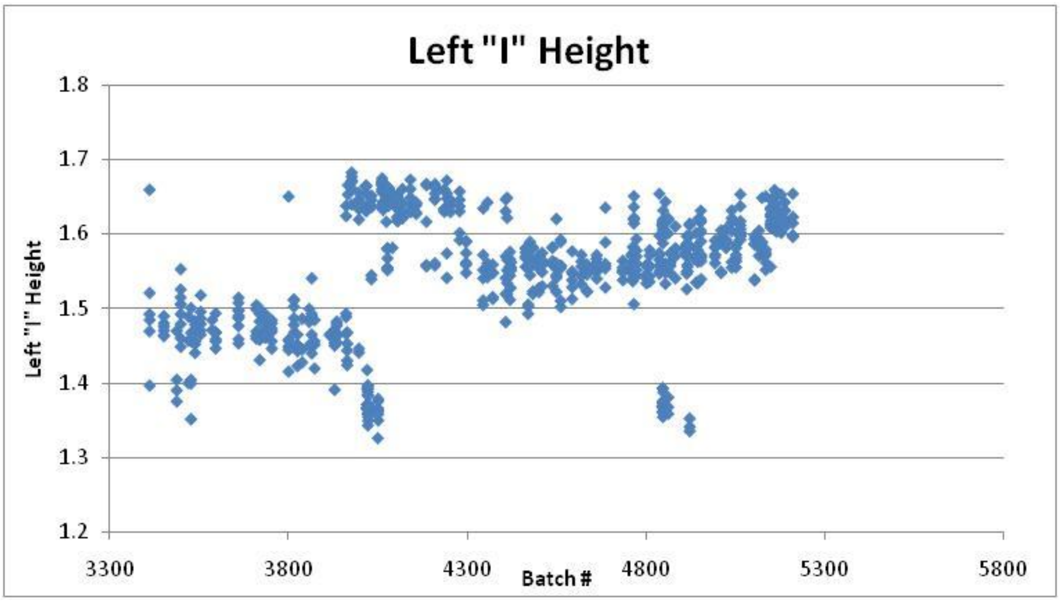
Several theories have been proposed regarding the fate of the Crewes:

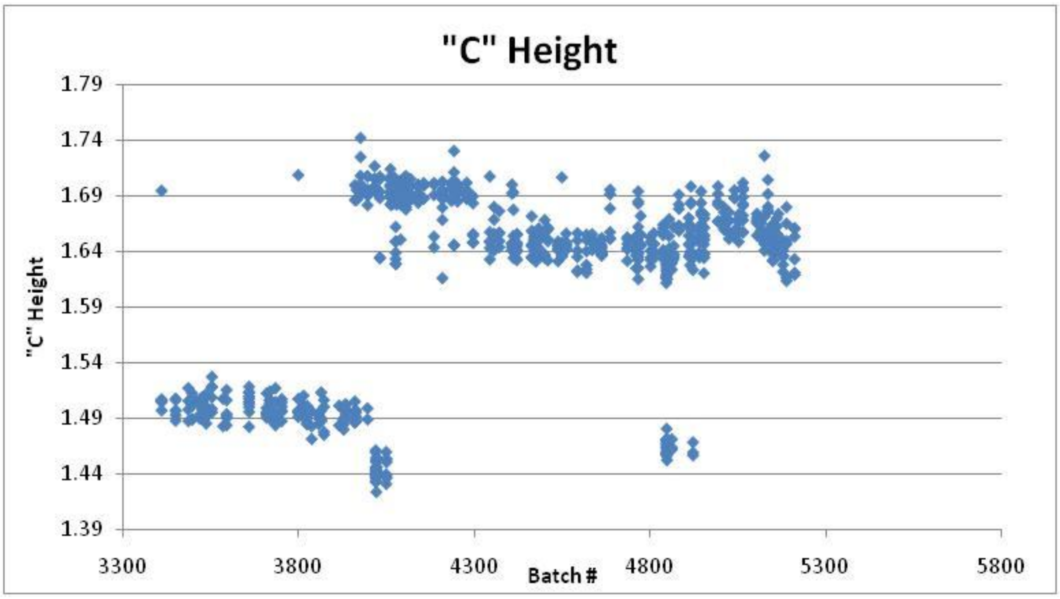
- British Author David Yallop strongly hinted in his 1978 book “Beyond Reasonable Doubt” that he believes that Mr Len Demler (Jeannette Crewe’s father) was responsible for the murders of Mr and Mrs Crewe [38].
- New Zealand journalist Mr Chris Birt suggests that Mr Demler was responsible for killing both victims as discussed in his 2001 book “The Final Chapter” [39].
- Investigative Journalist Mr Pat Booth (author of “Trial by Ambush”, 1975) suggests that the murder of Mr and Mrs Crewe was not a double-homicide, but instead was a murder-suicide. He proposed that Mrs Crewe killed Mr Crewe in self defence before killing herself. Furthermore, Mr Demler was responsible for dumping the bodies into the Waikato River [40].
- Ian Wishart (“Arthur Allan Thomas: The Inside Story”, 2010) has proposed two possibilities. The first of these suggests that Detective Johnson (one of the officers involved in the case) was responsible for the murders. The other possibility is that the son of a prominent New Zealand family, who worked in the area where the murders took place, was the murderer. However, Ian Wishart does not directly name the latter individual in his book [41].

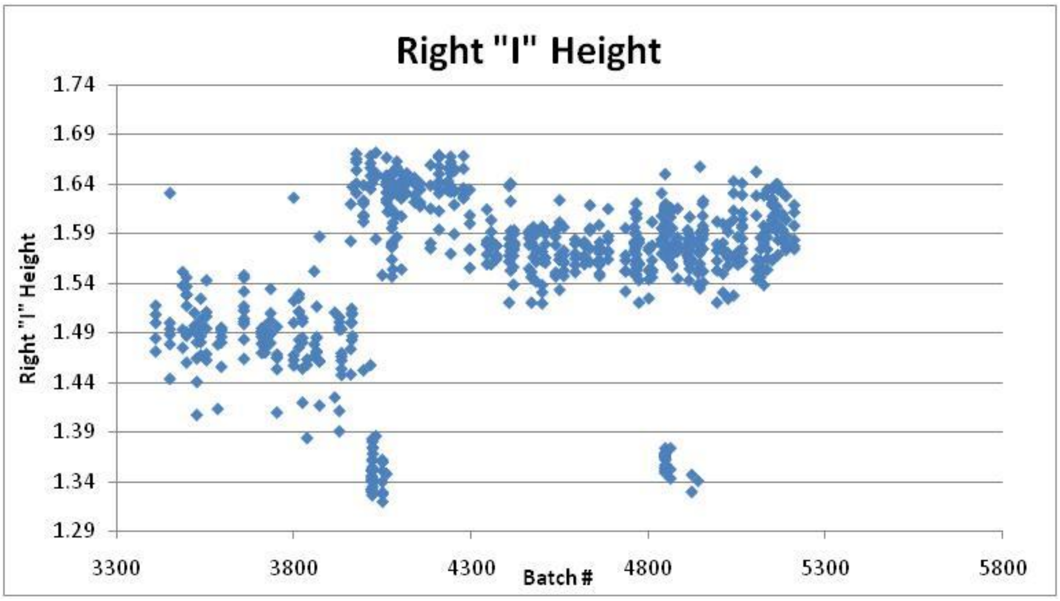
To this day, the murder of Mr and Mrs Crewe is the subject of significant debate and public interest. It remains one of the most high profile unsolved cases in New Zealand’s history.

APPENDIX II

Following are the graphs for each data transformation versus batch number for all of the collected data. Graphs have also been included for some of the standardised coordinates and diameters of the heads of the cartridges across the vertical and horizontal planes.



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1.64
1.59
1.54
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1.39
1.34
1.29
Right "I" Height
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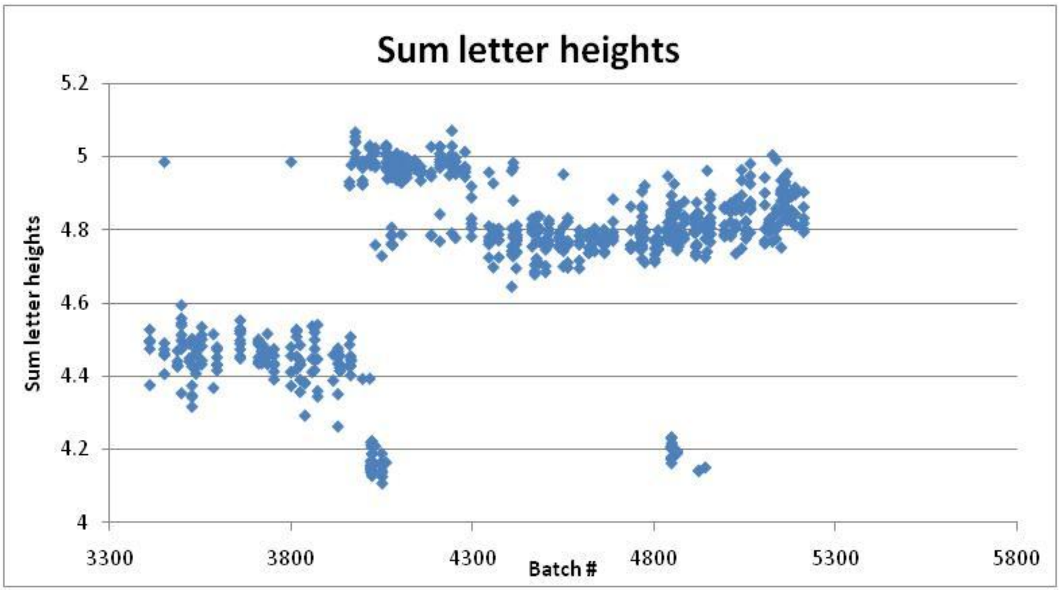
3800
4300
Batch #
4800
5300
5800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5
4.8
4.6
4.4
4.2
4
Sum letter heights
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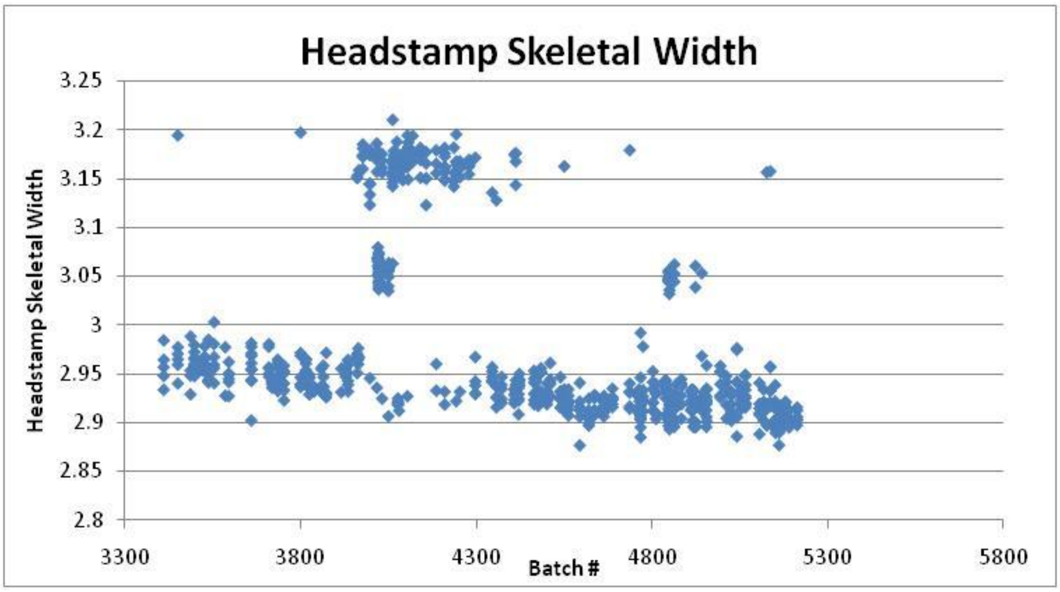
3800
4300
Batch #
4800
5300
5800


Headstamp Skeletal Width
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3.2
3.15
3.1
3.05
3
2.95
2.9
2.85
2.8
Headstamp Skeletal Width
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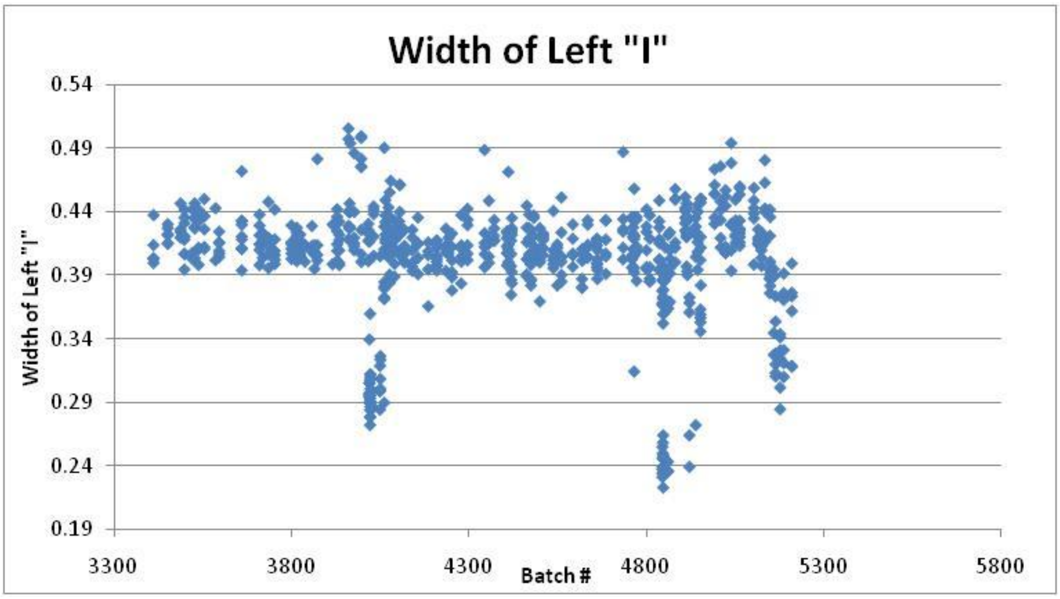
3800
4300
Batch #
4800
5300
5800


Width of Left "I"
Width of Left "I"
Batch #
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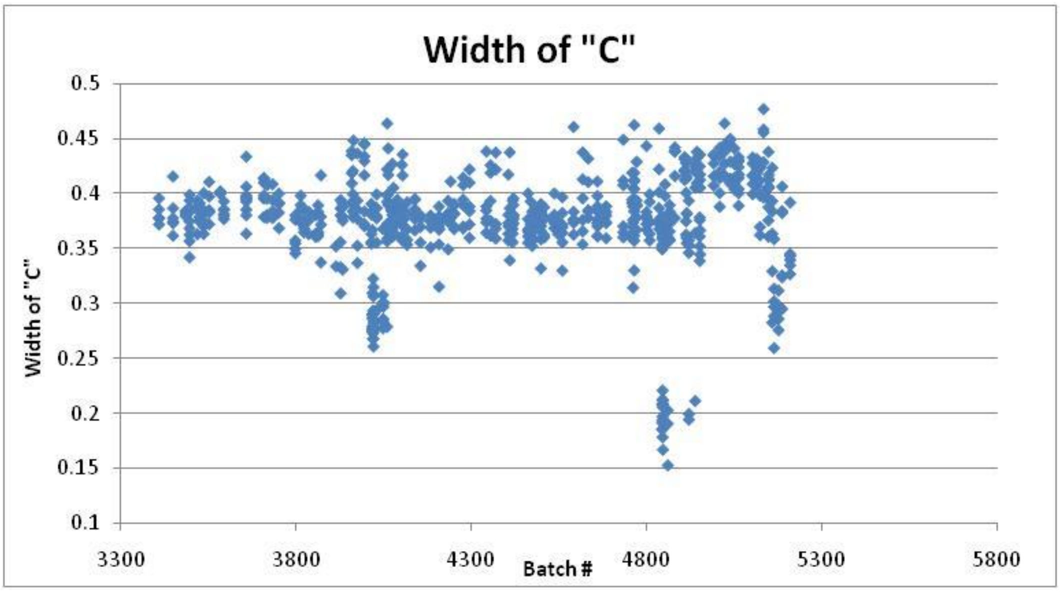
4800
5300
5800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Width of "C"
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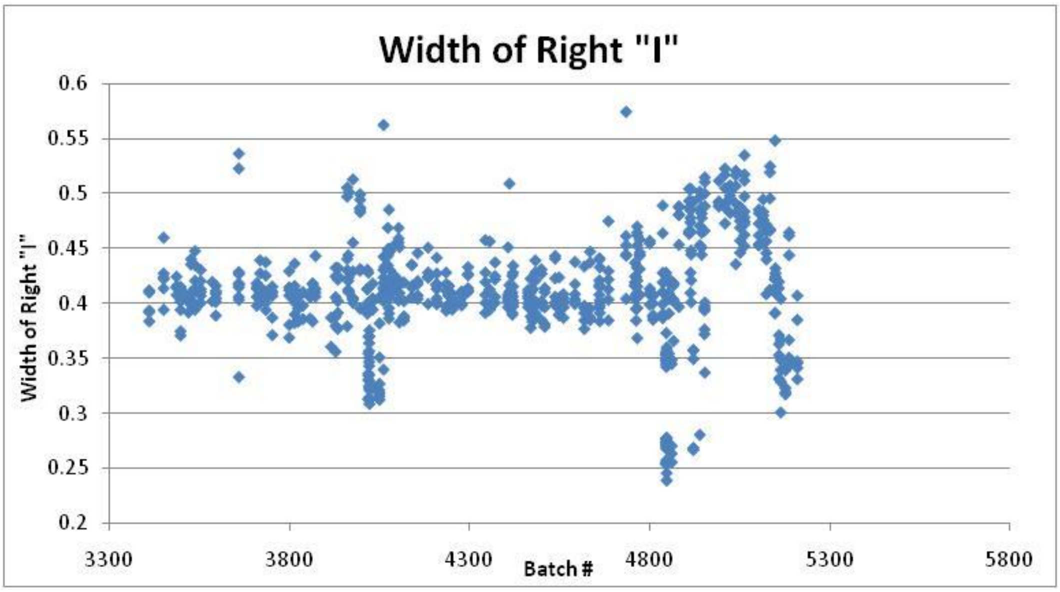
0.1
3300
3800
4300
4800
5300
5800


Width of Right "I"
Width of Right "I"
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0.35
0.3
0.25
0.2
3300
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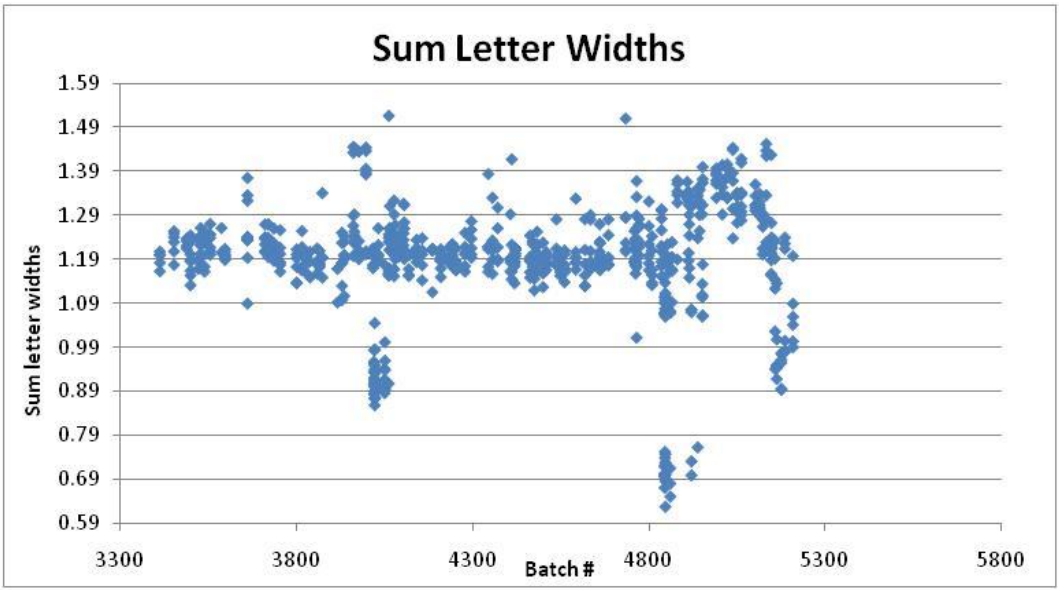
4300
4800
5300
5800


Sum Letter Widths
Sum letter widths
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1.39
1.29
1.19
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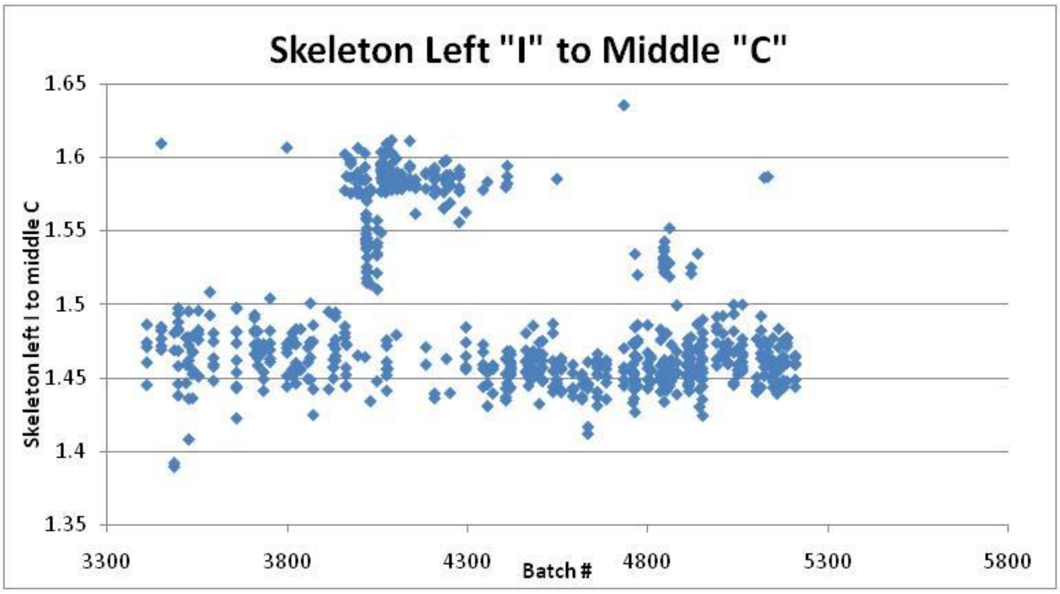
0.79
0.69
0.59
3300
3800
4300
Batch #
4800
5300
5800


Skeleton Left "I" to Middle "C"
Skeleton left I to middle C
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1.6
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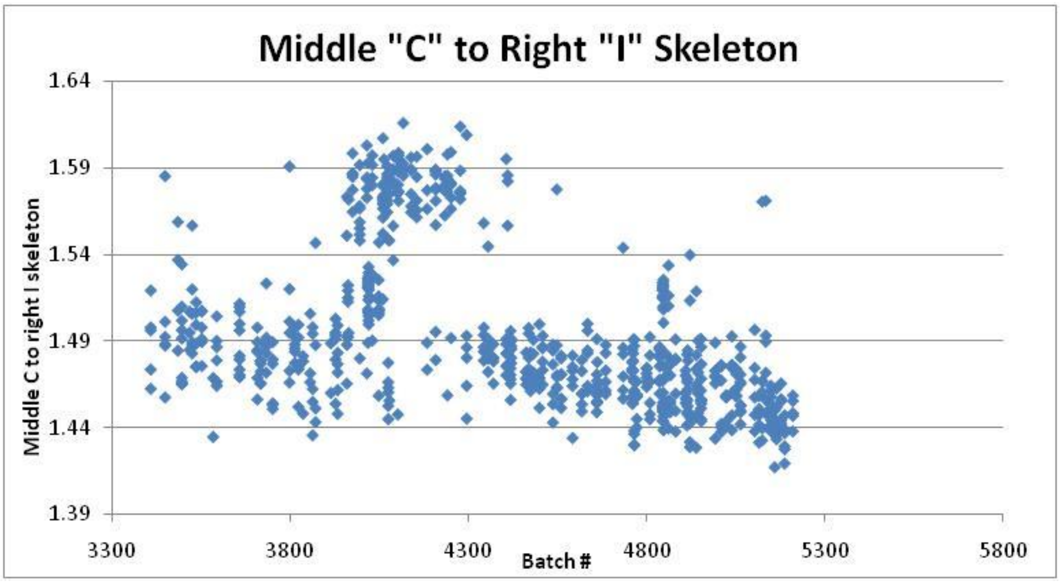
1.5
1.45
1.4
1.35
3300
3800
4300
Batch #
4800
5300
5800


Middle "C" to Right "I" Skeleton
Middle C to right I skeleton
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1.54
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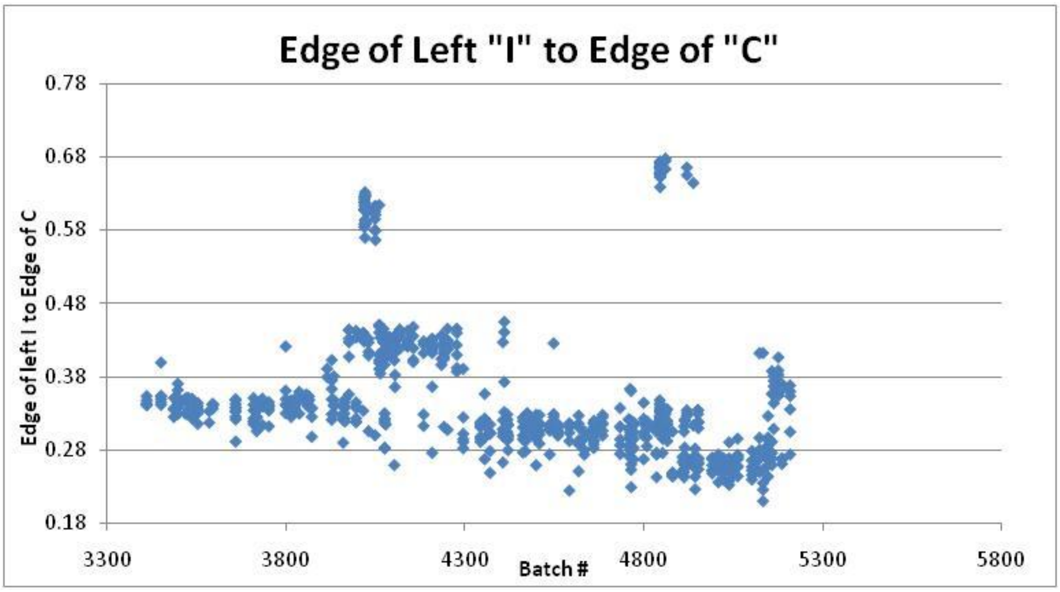
3800
4300
Batch #
4800
5300
5800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0.68
0.58
0.48
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0.18
Edge of left I to Edge of C
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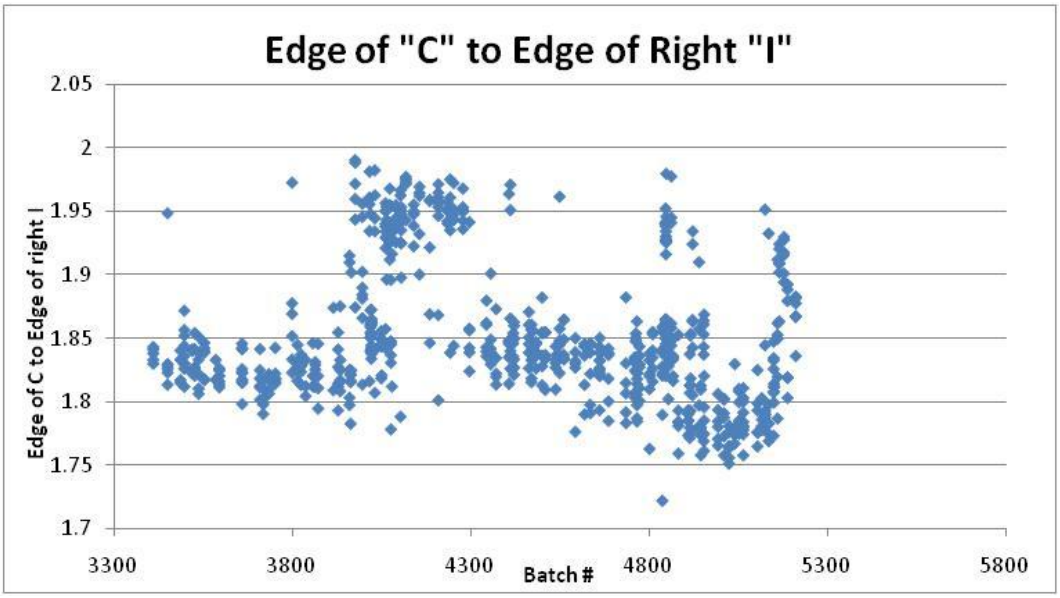
3800
4300
4800
5300
5800
Batch #


Edge of "C" to Edge of Right "I"
2.05
2
1.95
1.9
1.85
1.8
1.75
1.7
Edge of C to Edge of right I
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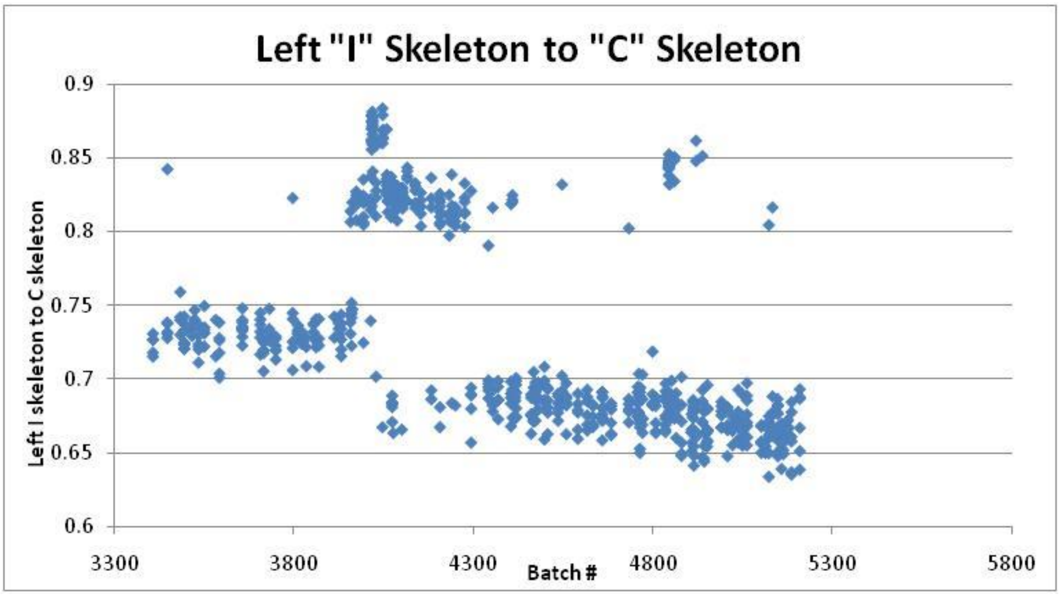
4800
5300
5800
Batch #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0.85
0.8
0.75
0.7
0.65
0.6
Left I skeleton to C skeleton
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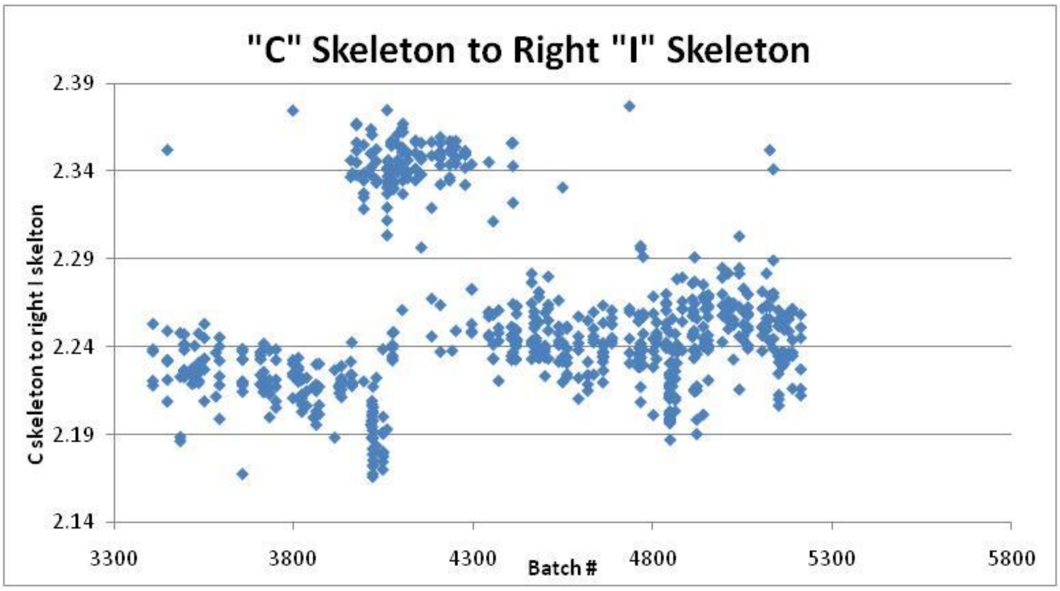
3800
4300
4800
5300
5800
Batch #


"C" Skeleton to Right "I" Skeleton
C skeleton to right I skelton
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2.29
2.24
2.19
2.14
3300
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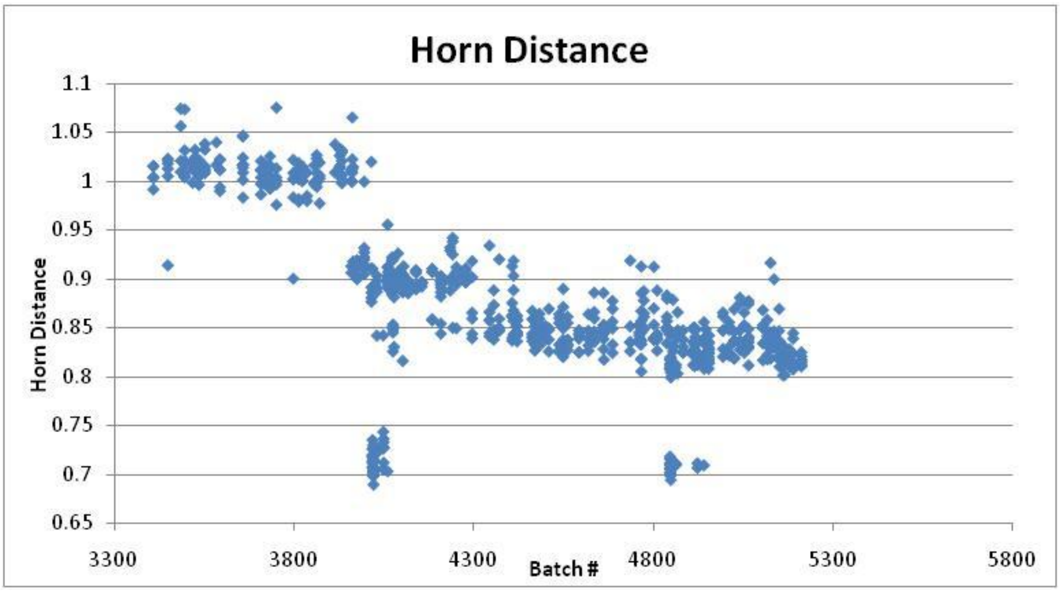
4800
5300
5800
Batch #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Horn Distance
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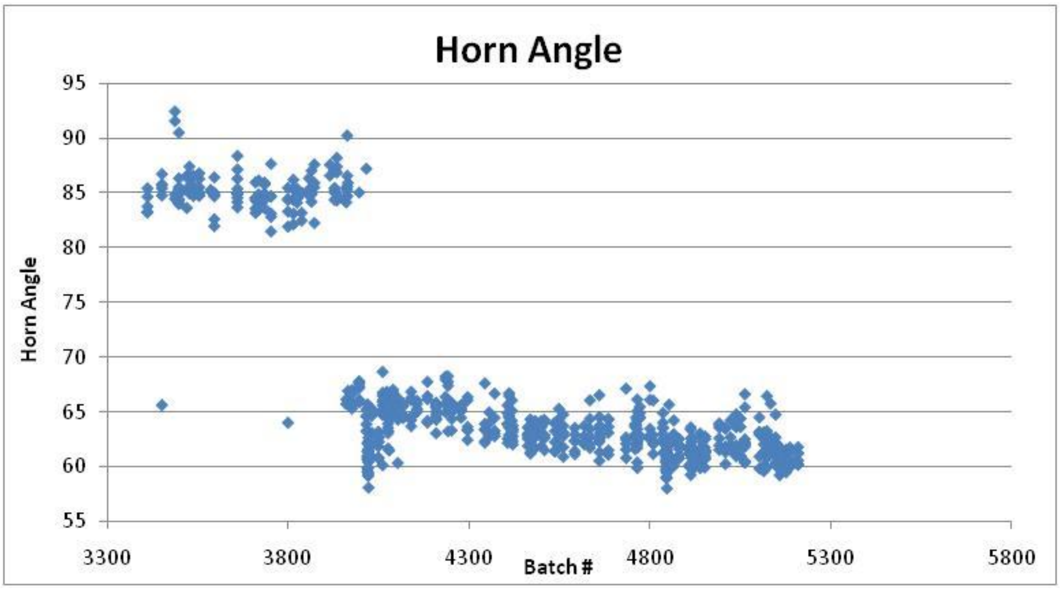
3800
4300
4800
5300
5800
Batch #


Horn Angle
Horn Angle
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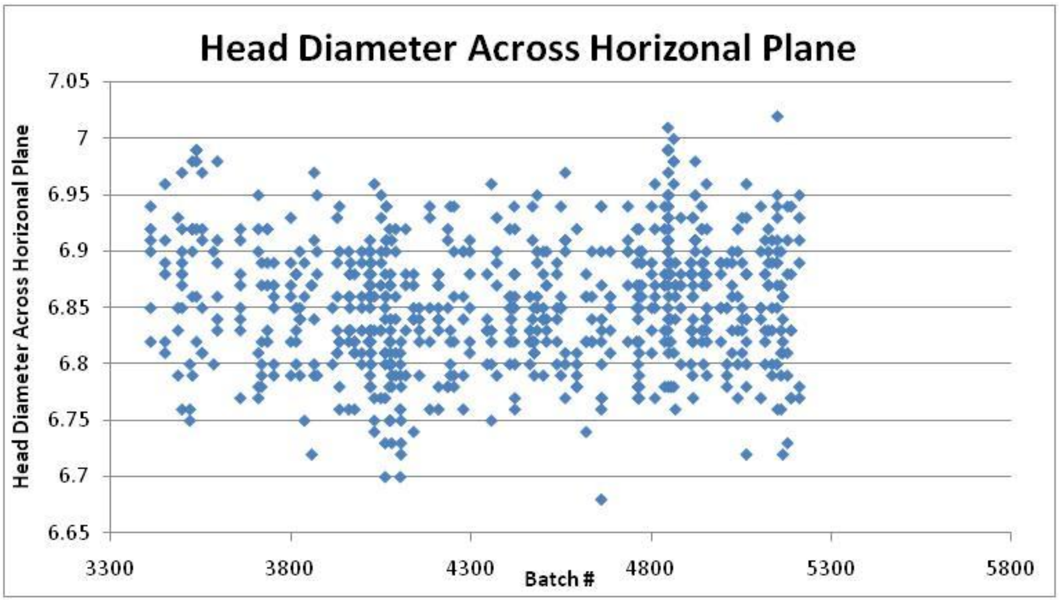
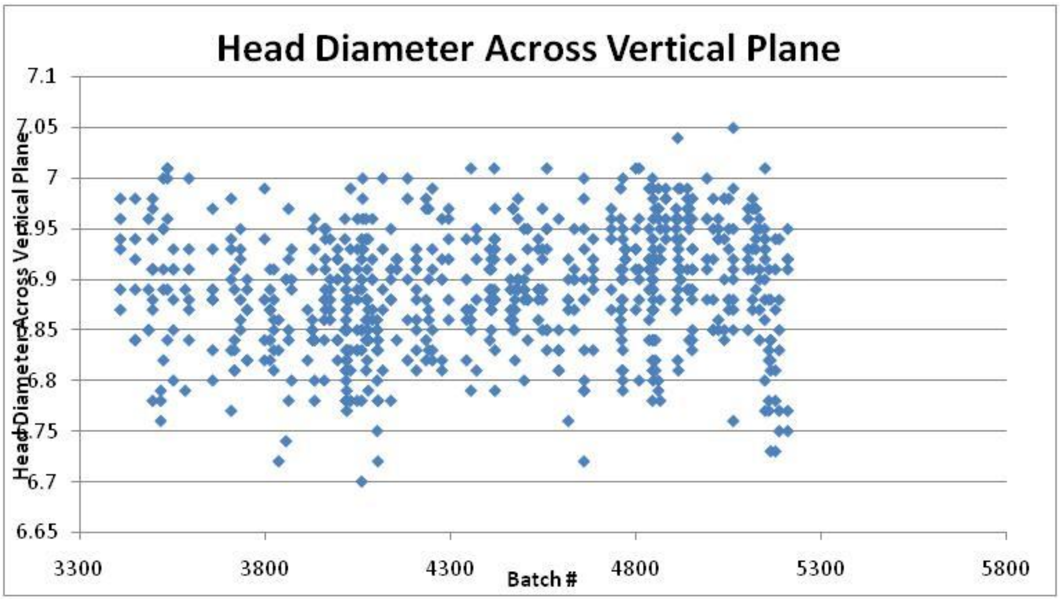
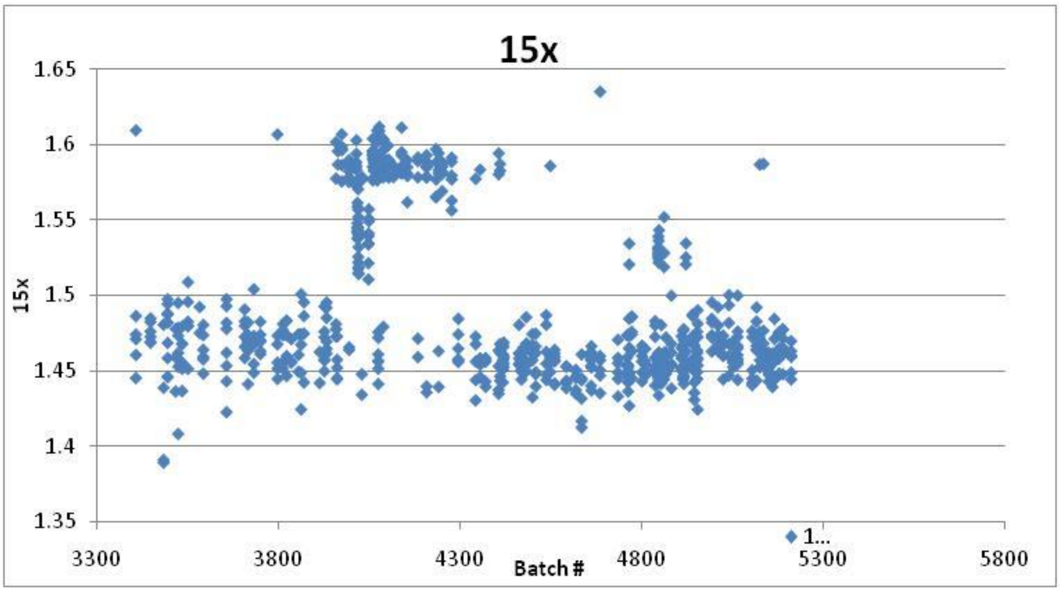
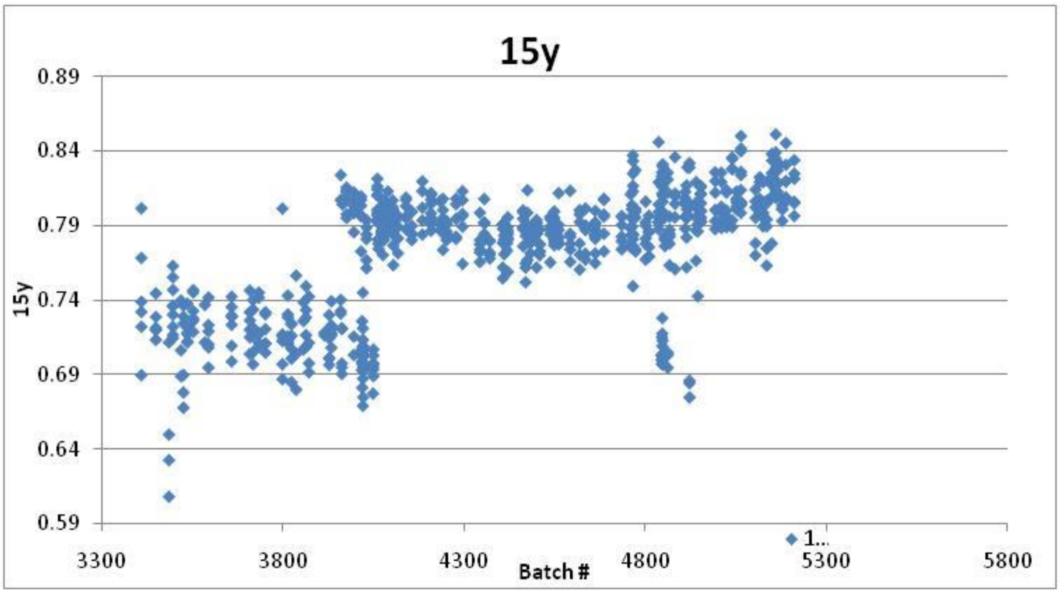
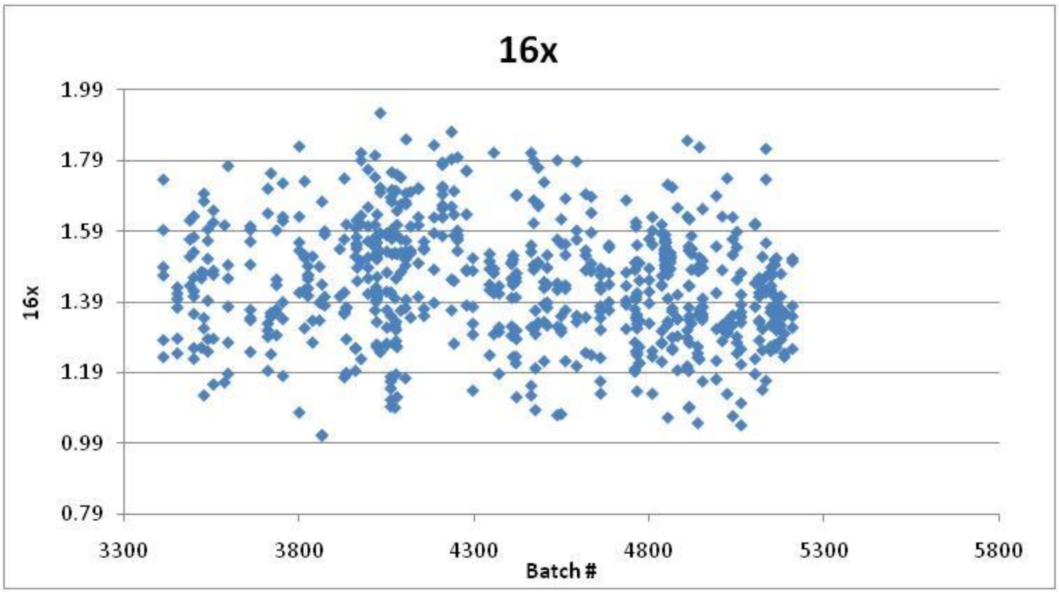
90
85
80
75
70
65
60
55
3300
3800
4300
4800
5300
5800
Batch #

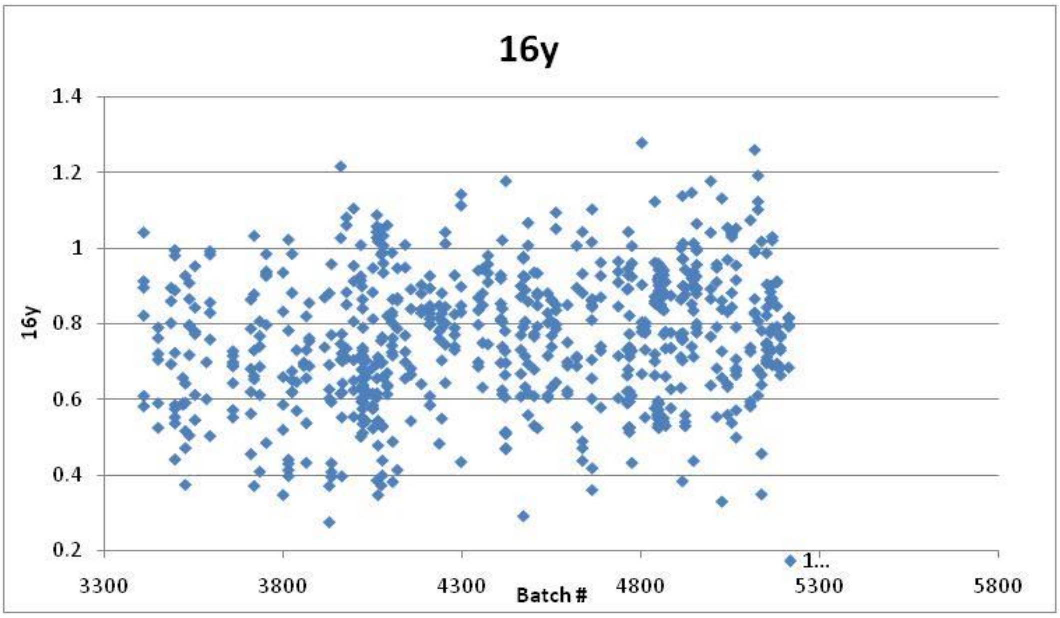

Head Diameter Across Horizonal Plane
Head Diameter Across Horizonal Plane
Batch #
7.05
7
6.95
6.9
6.85
6.8
6.75
6.7
6.65
3300
3800
4300
4800
5300
5800


Head Diameter Across Vertical Plane
Head Diameter Across Vertical Plane
Batch #
7.1
7.05
7
6.95
6.9
6.85
6.8
6.75
6.7
6.65
3300
3800
4300
4800
5300
5800


15x
15x
Batch #
1.65
1.6
1.55
1.5
1.45
1.4
1.35
3300
3800
4300
4800
5300
5800
1...

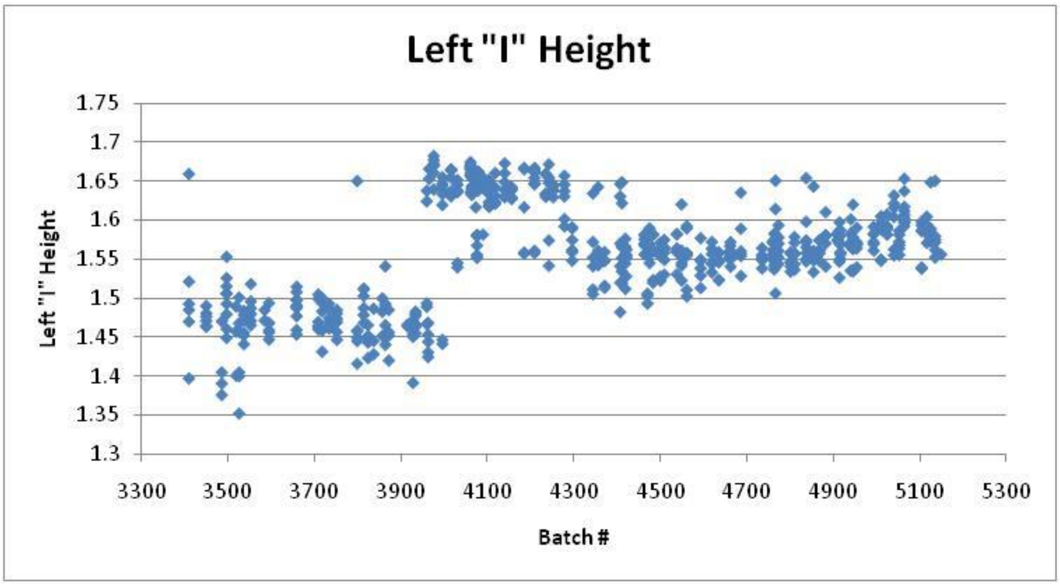

15y
0.89
0.84
0.79
0.74
0.69
0.64
0.59
15y
3300
3800
4300
4800
5300
5800
Batch #
1...

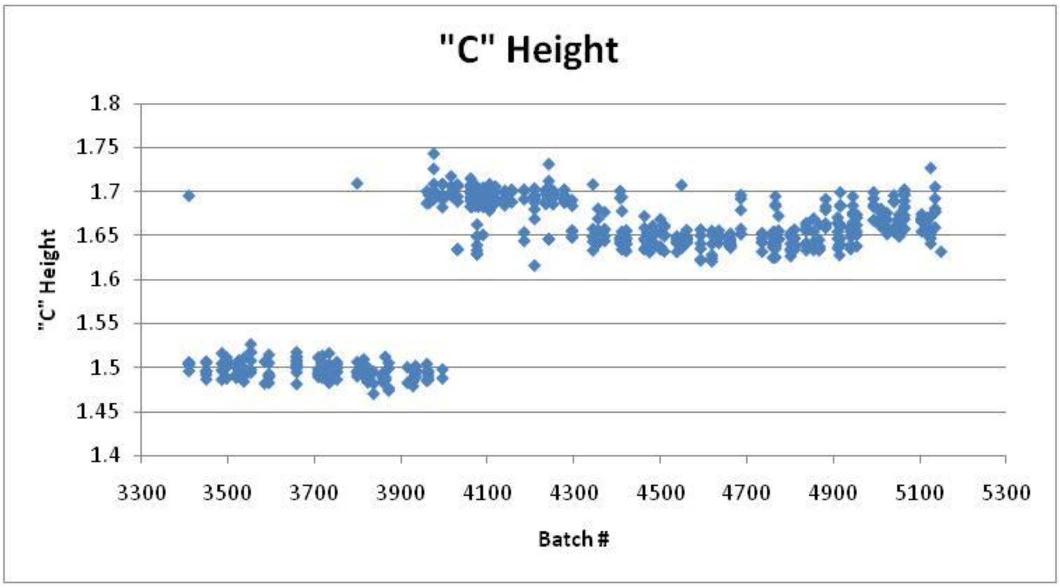

16x
1.99
1.79
1.59
1.39
1.19
0.99
0.79
16x
3300
3800
4300
4800
5300
5800
Batch #

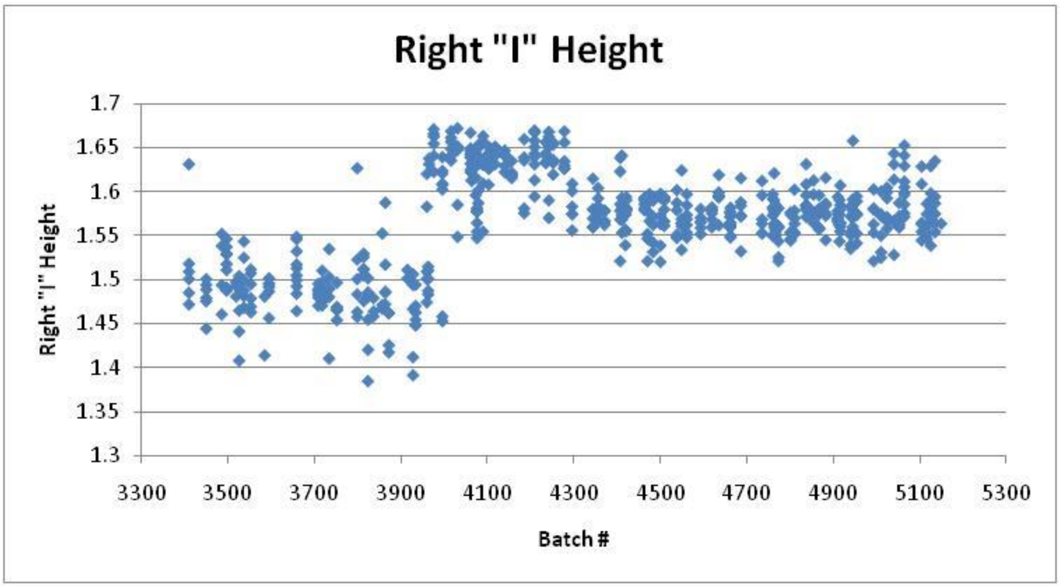

16y
1.4
1.2
1
0.8
0.6
0.4
0.2
16y
3300
3800
4300
4800
5300
5800
Batch #
1...

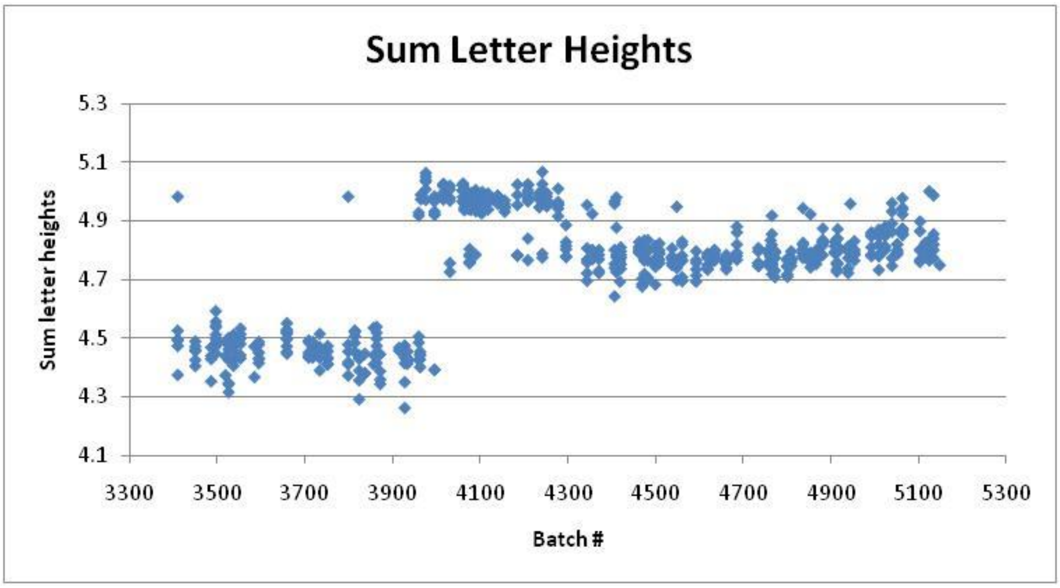
APPENDIX III

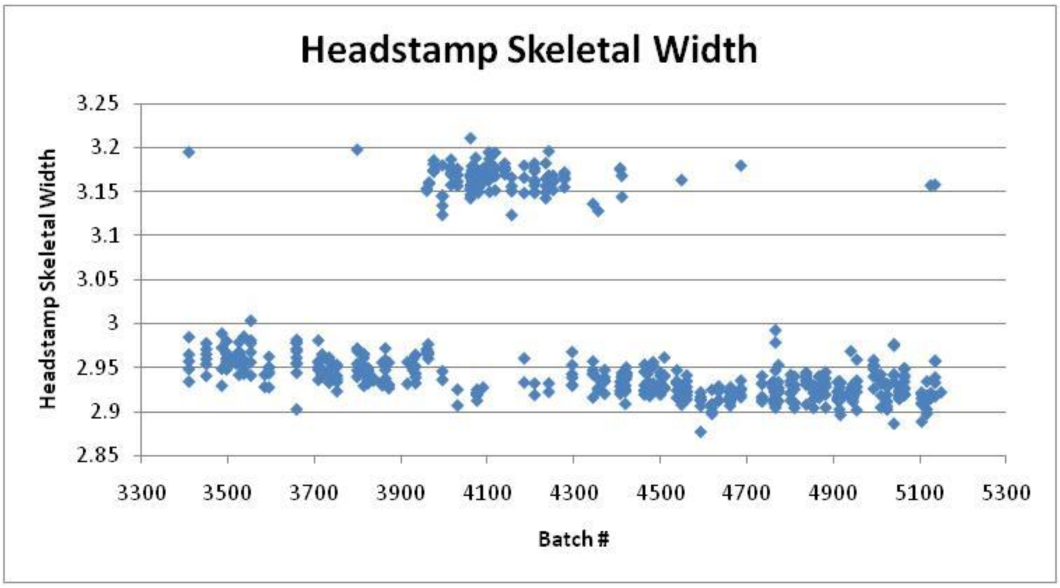
Following are the graphs for each data transformation versus batch number for the dry-primed cartridges. Graphs have also been included for some of the standardised coordinates and diameters of the heads of the cartridges across the vertical and horizontal planes.

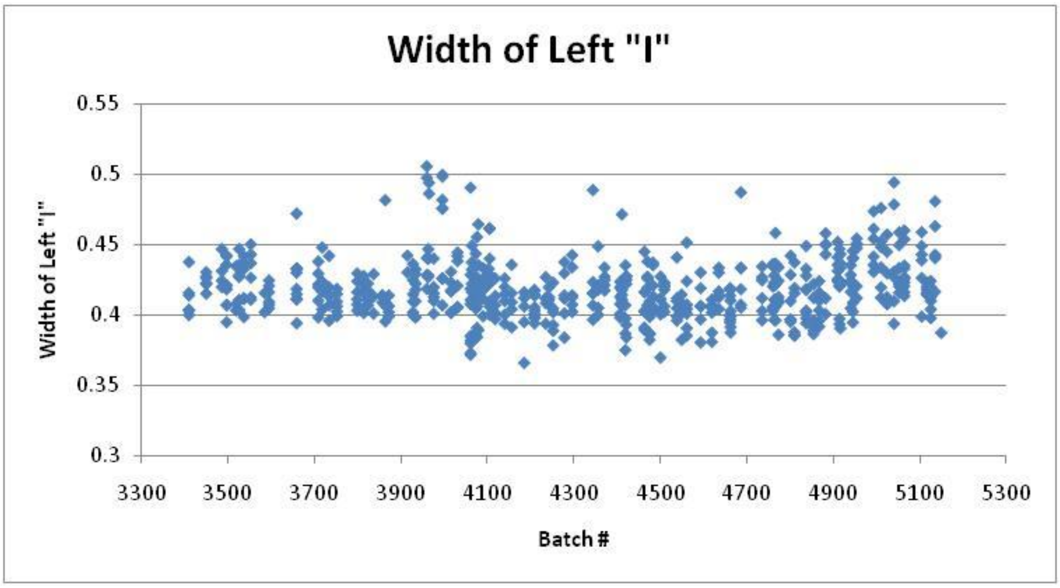


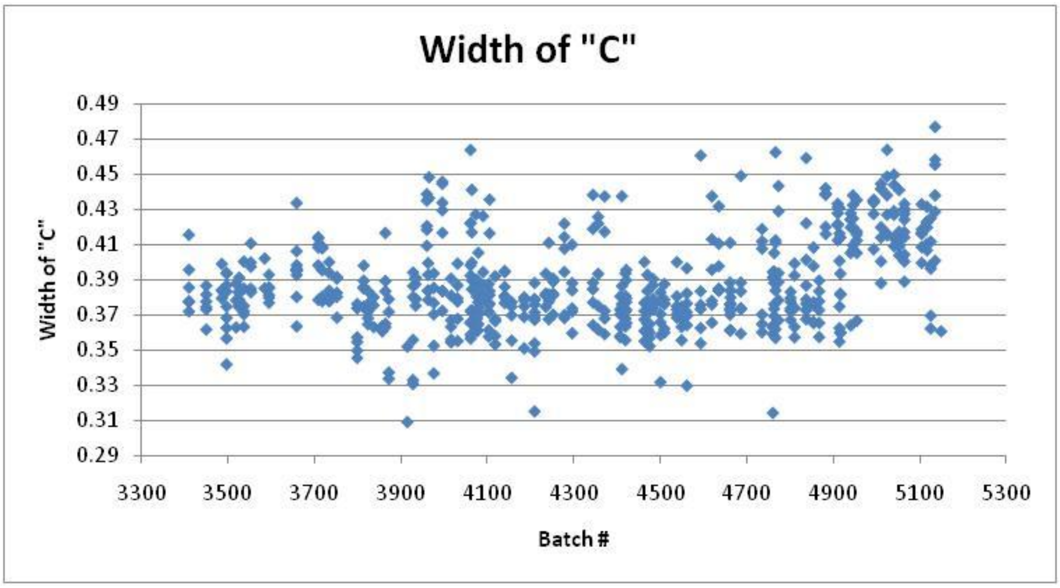


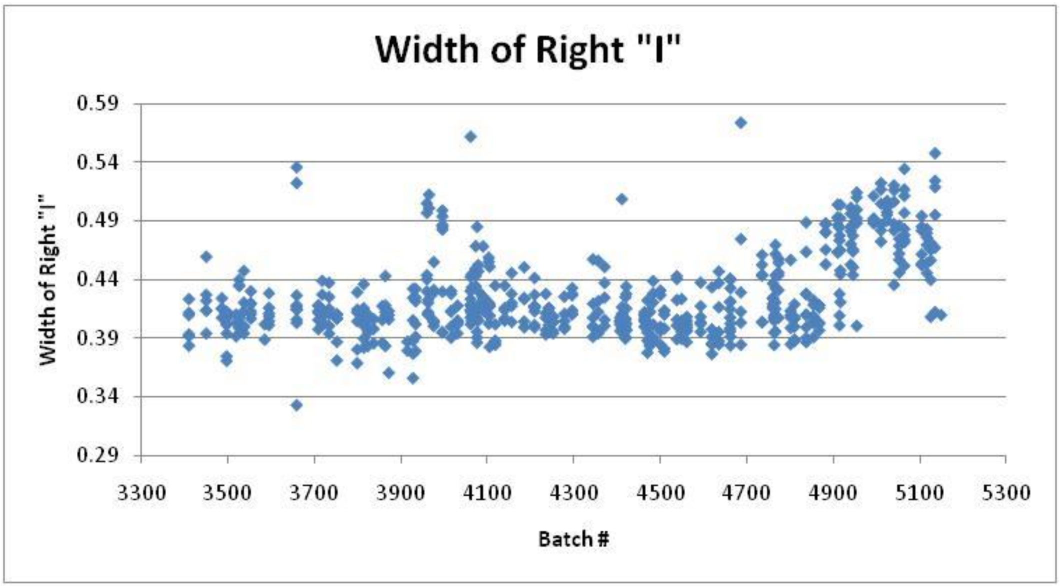

Right "I" Height
Right "I" Height
Batch #

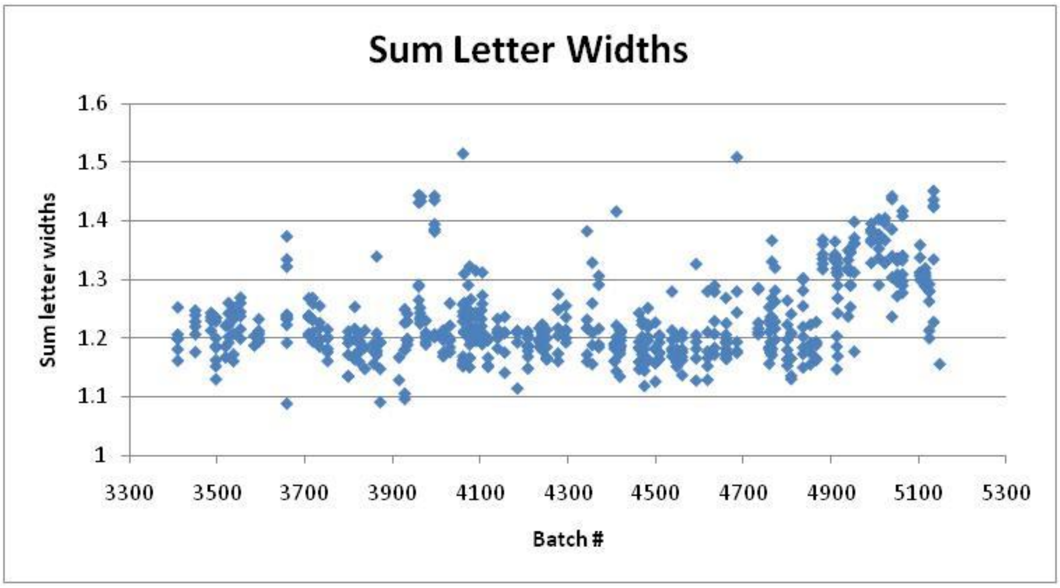

Sum Letter Heights
Sum letter heights
Batch #

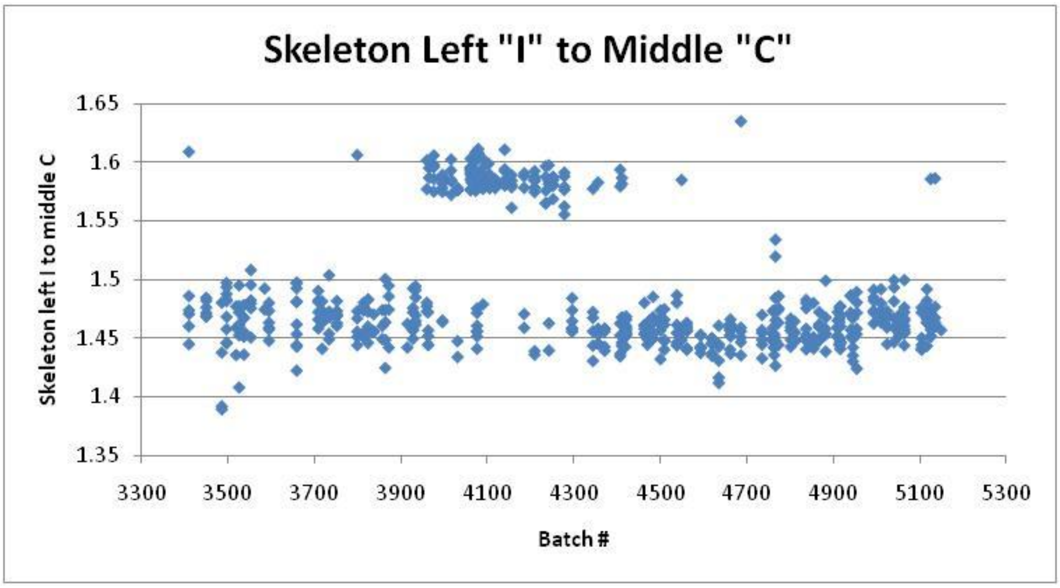

Headstamp Skeletal Width
Headstamp Skeletal Width
Batch #

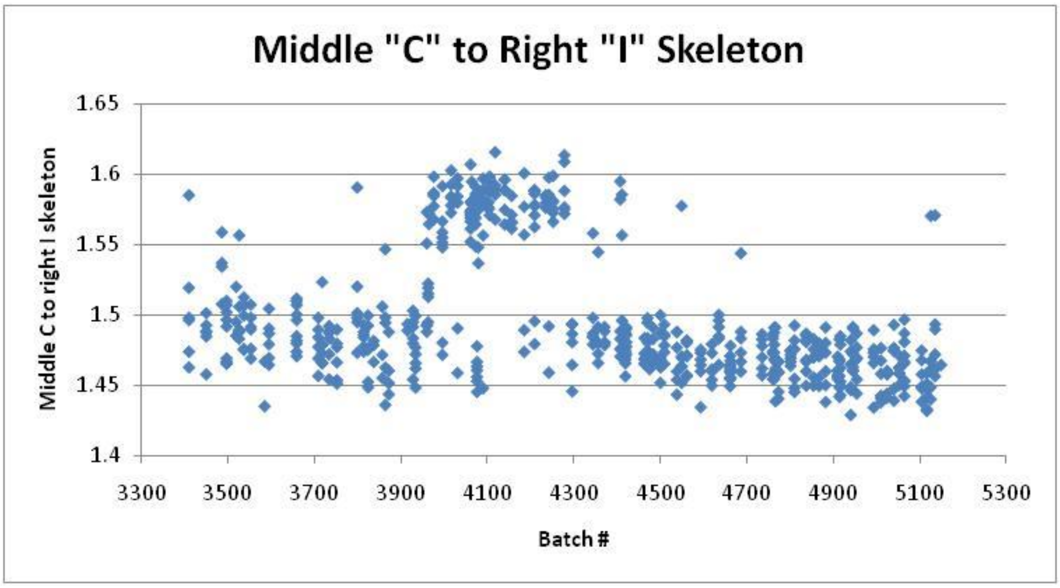

Width of Left "I"
Width of Left "I"
0.55
0.5
0.45
0.4
0.35
0.3
3300
3500
3700
3900
4100
4300
4500
4700
4900
5100
5300
Batch #

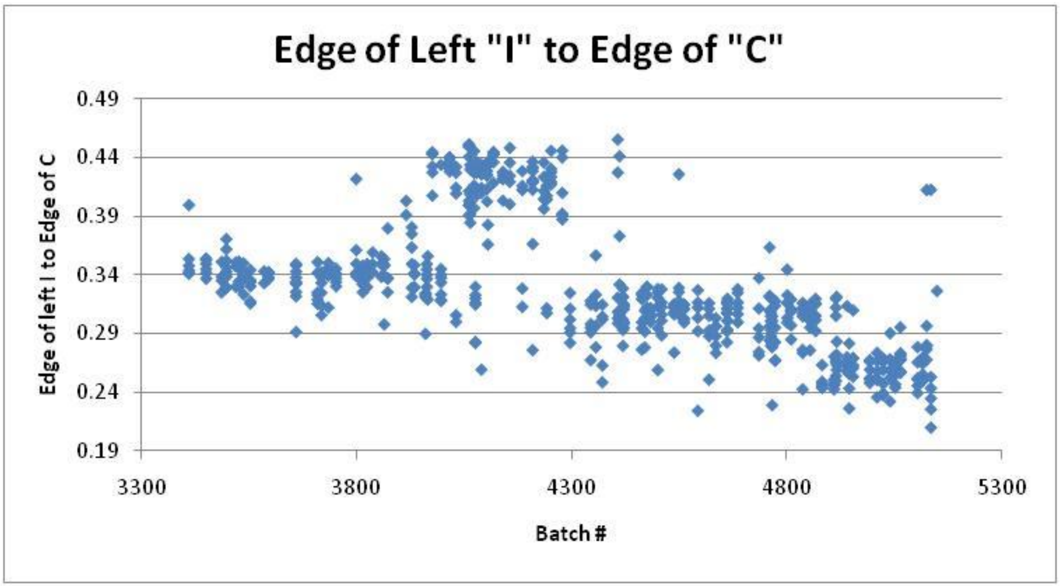

Width of "C"
Width of "C"
0.49
0.47
0.45
0.43
0.41
0.39
0.37
0.35
0.33
0.31
0.29
3300
3500
3700
3900
4100
4300
4500
4700
4900
5100
5300
Batch #

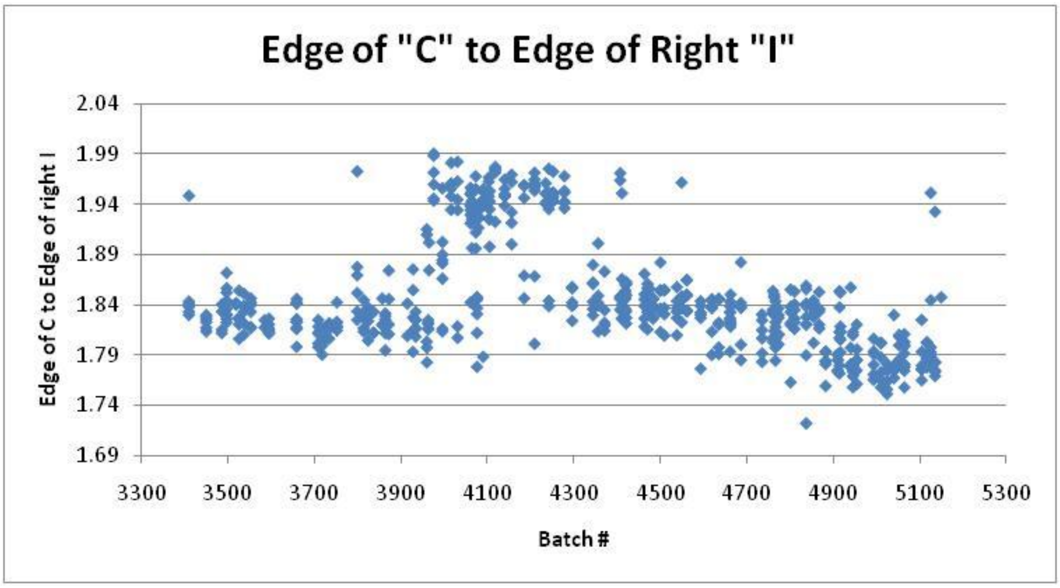

Width of Right "I"
Width of Right "I"
0.59
0.54
0.49
0.44
0.39
0.34
0.29
3300
3500
3700
3900
4100
4300
4500
4700
4900
5100
5300
Batch #

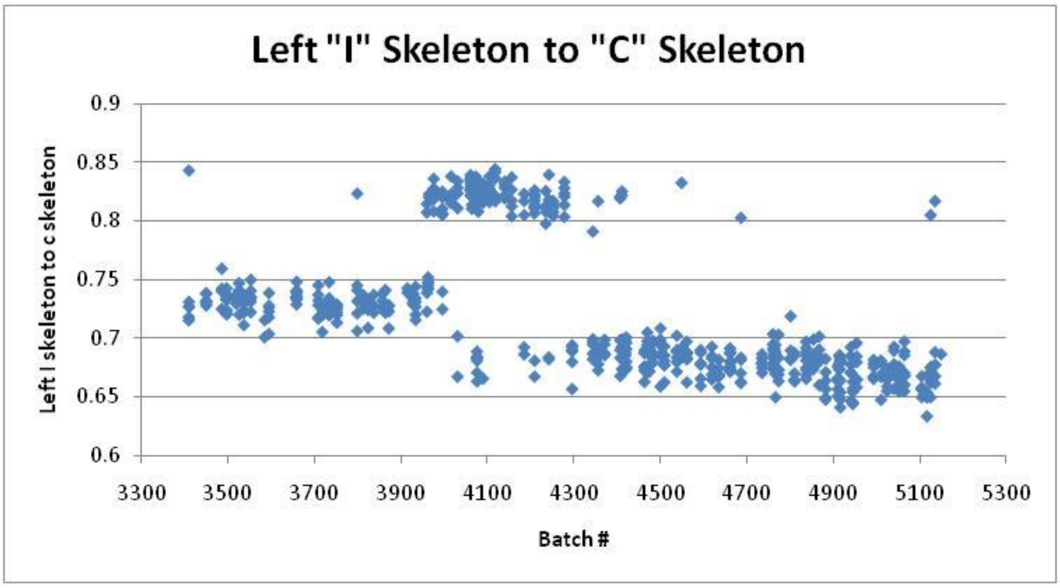

Sum Letter Widths
Sum letter widths
1.6
1.5
1.4
1.3
1.2
1.1
1
3300
3500
3700
3900
4100
4300
4500
4700
4900
5100
5300
Batch #

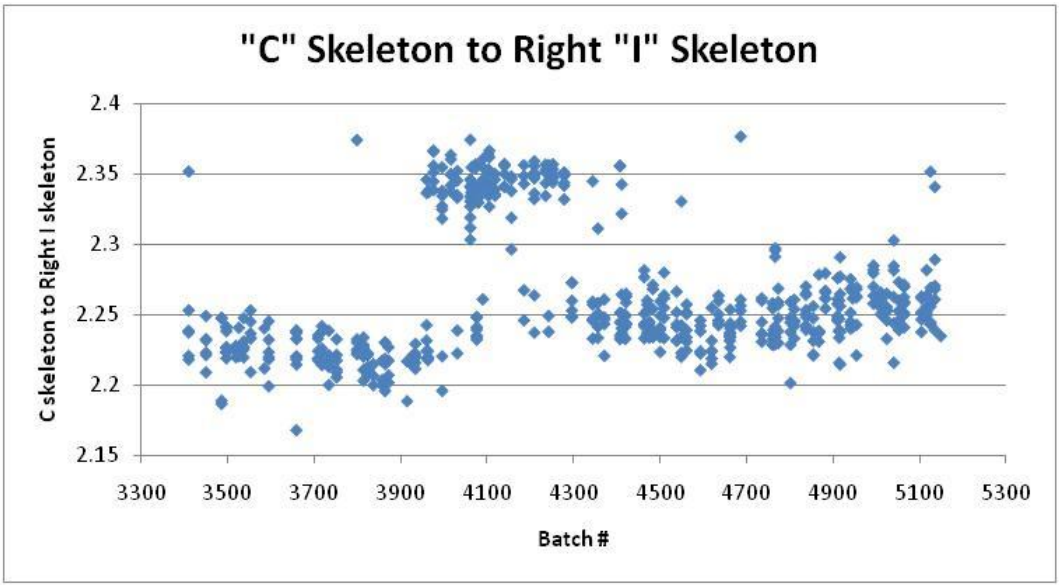

Skeleton Left "I" to Middle "C"
Skeleton left I to middle C
1.65
1.6
1.55
1.5
1.45
1.4
1.35
3300
3500
3700
3900
4100
4300
4500
4700
4900
5100
5300
Batch #

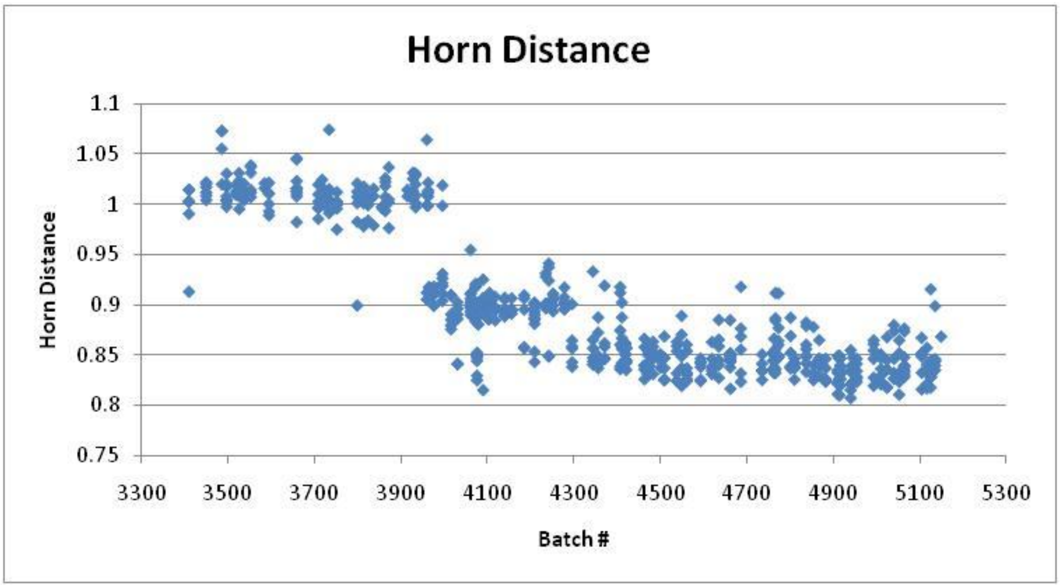

Middle "C" to Right "I" Skeleton
Middle C to right I skeleton
1.65
1.6
1.55
1.5
1.45
1.4
3300
3500
3700
3900
4100
4300
4500
4700
4900
5100
5300
Batch #

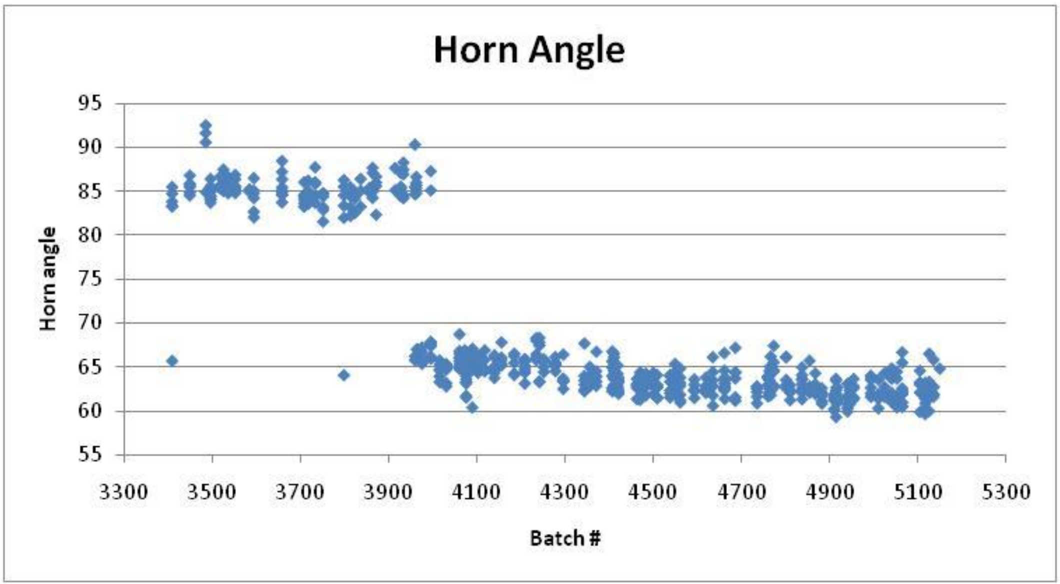

Edge of Left "I" to Edge of "C"
Edge of left I to Edge of C
0.49
0.44
0.39
0.34
0.29
0.24
0.19
3300
3800
4300
4800
5300
Batch #

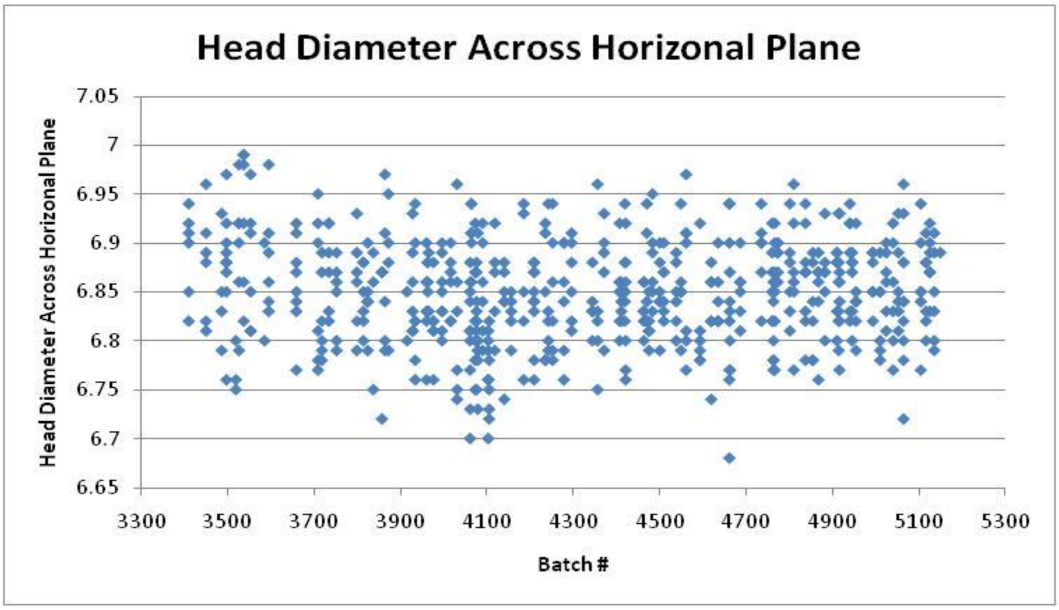

Edge of "C" to Edge of Right "I"
Edge of C to Edge of right I
2.04
1.99
1.94
1.89
1.84
1.79
1.74
1.69
3300
3500
3700
3900
4100
4300
4500
4700
4900
5100
5300
Batch #

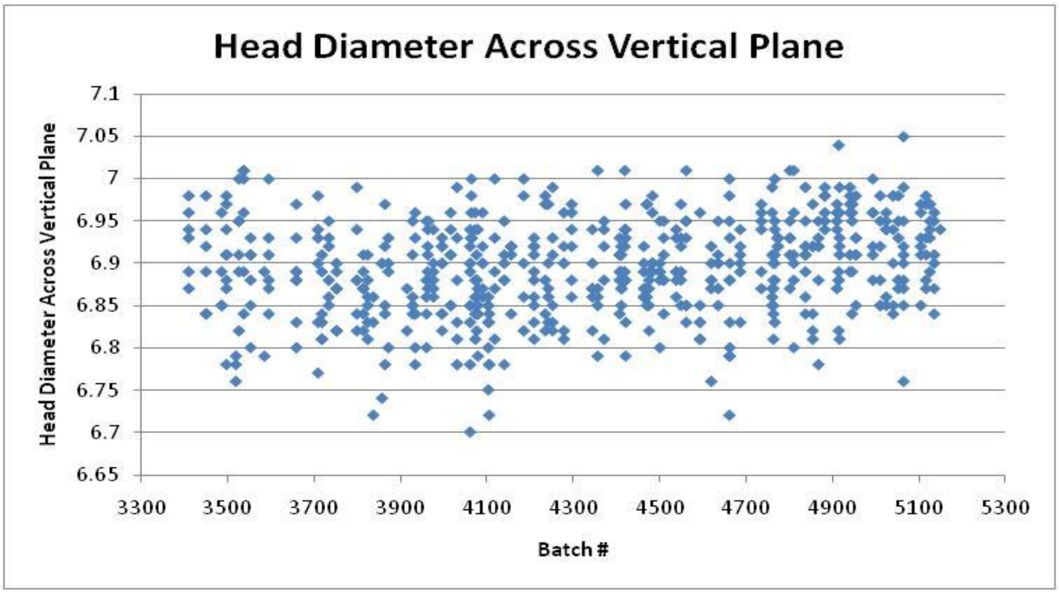

Left "I" Skeleton to "C" Skeleton
Left I skeleton to c skeleton
0.9
0.85
0.8
0.75
0.7
0.65
0.6
3300
3500
3700
3900
4100
4300
4500
4700
4900
5100
5300
Batch #

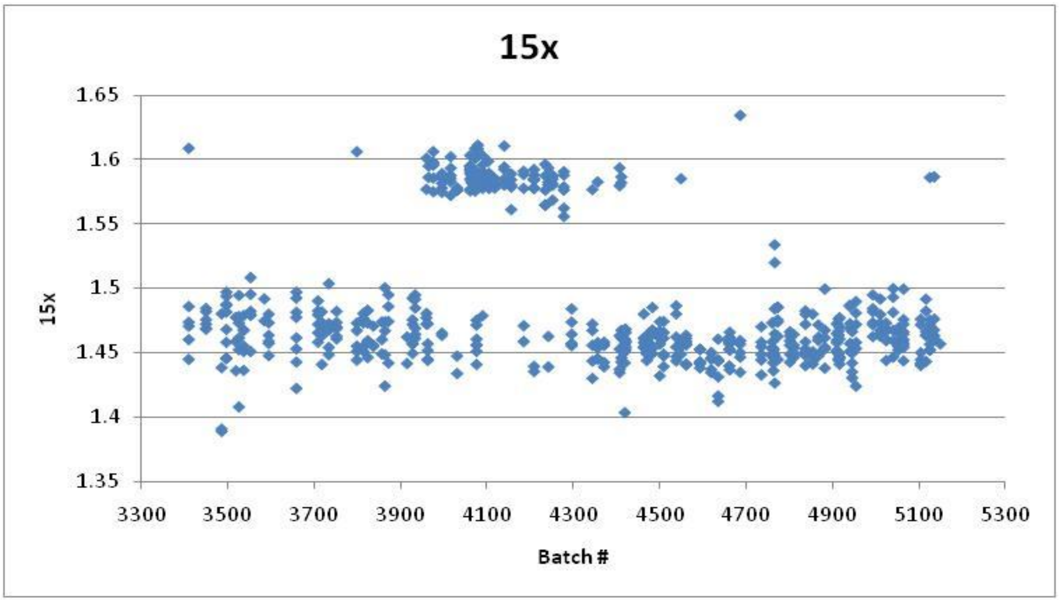

"C" Skeleton to Right "I" Skeleton
C skeleton to Right I skeleton
2.4
2.35
2.3
2.25
2.2
2.15
3300 3500 3700 3900 4100 4300 4500 4700 4900 5100 5300
Batch #

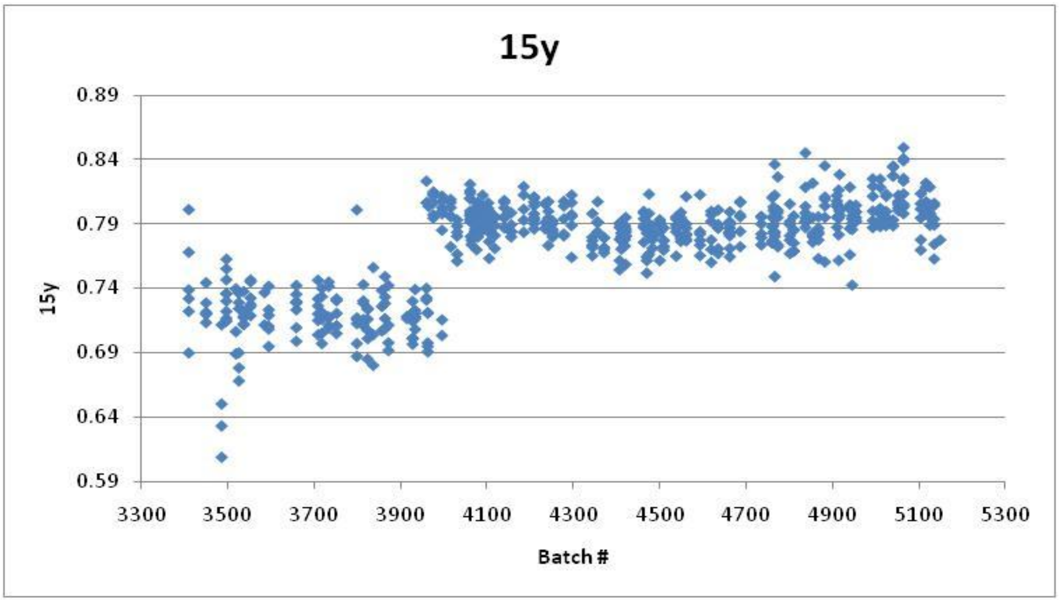

Horn Distance
Horn Distance
1.1
1.05
1
0.95
0.9
0.85
0.8
0.75
3300 3500 3700 3900 4100 4300 4500 4700 4900 5100 5300
Batch #

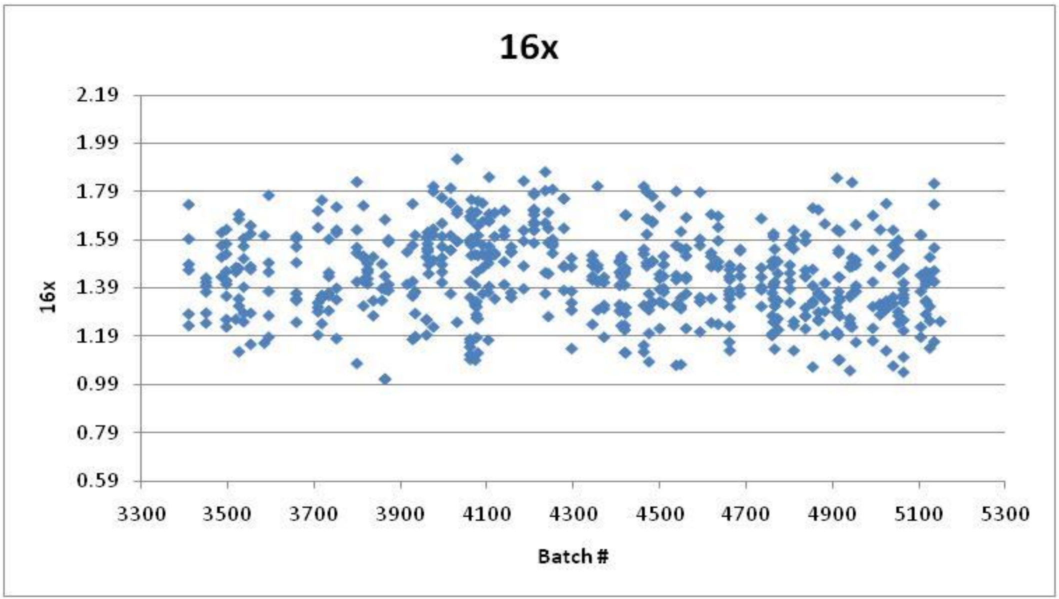

Horn Angle
Horn angle
95
90
85
80
75
70
65
60
55
3300 3500 3700 3900 4100 4300 4500 4700 4900 5100 5300
Batch #

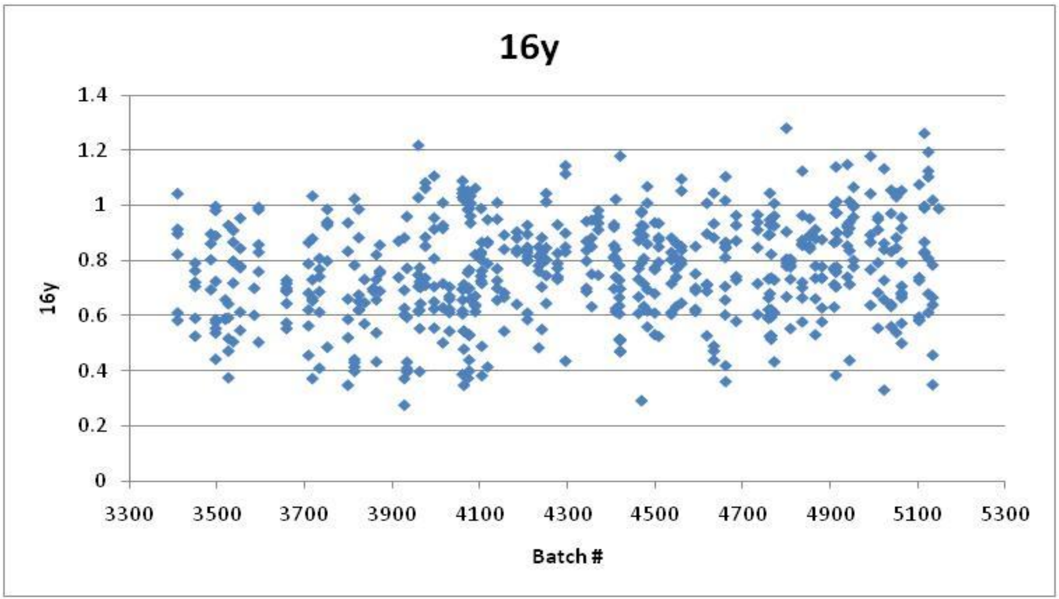

Head Diameter Across Horizonal Plane
Head Diameter Across Horizonal Plane
7.05
7
6.95
6.9
6.85
6.8
6.75
6.7
6.65
3300
3500
3700
3900
4100
4300
4500
4700
4900
5100
5300
Batch #


Head Diameter Across Vertical Plane
Head Diameter Across Vertical Plane
7.1
7.05
7
6.95
6.9
6.85
6.8
6.75
6.7
6.65
3300
3500
3700
3900
4100
4300
4500
4700
4900
5100
5300
Batch #


15x
15x
1.65
1.6
1.55
1.5
1.45
1.4
1.35
3300
3500
3700
3900
4100
4300
4500
4700
4900
5100
5300
Batch #

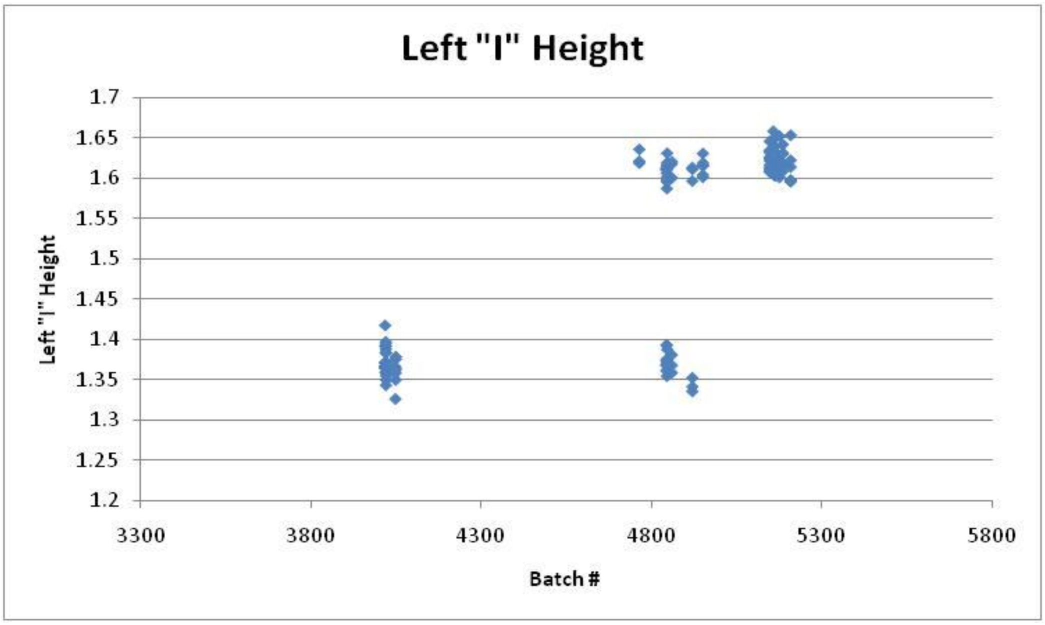

15y
0.89
0.84
0.79
0.74
0.69
0.64
0.59
15y
3300 3500 3700 3900 4100 4300 4500 4700 4900 5100 5300
Batch #

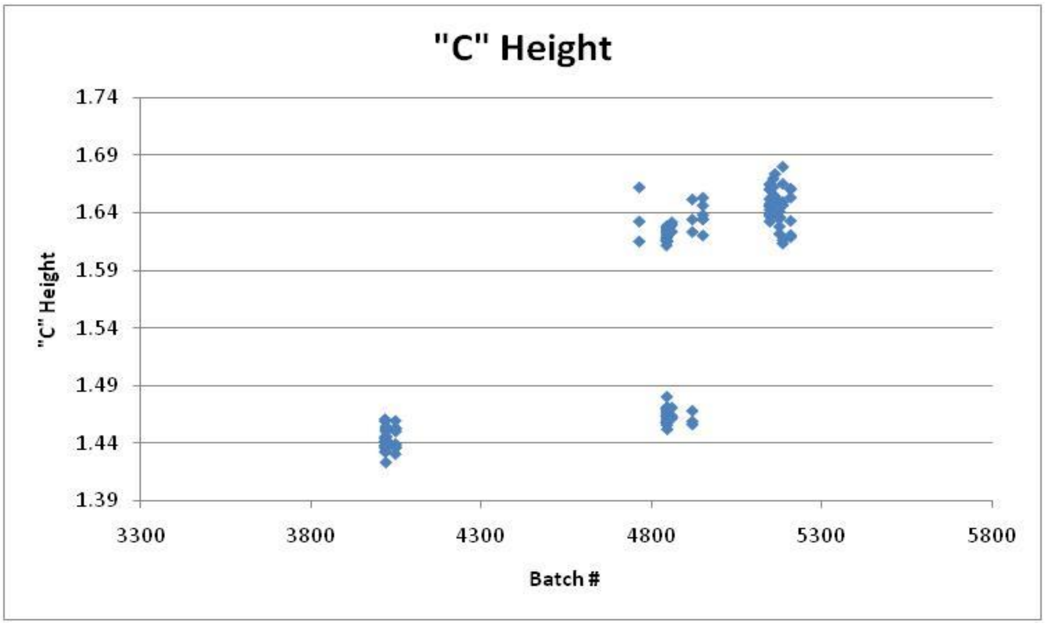

16x
2.19
1.99
1.79
1.59
1.39
1.19
0.99
0.79
0.59
16x
3300 3500 3700 3900 4100 4300 4500 4700 4900 5100 5300
Batch #

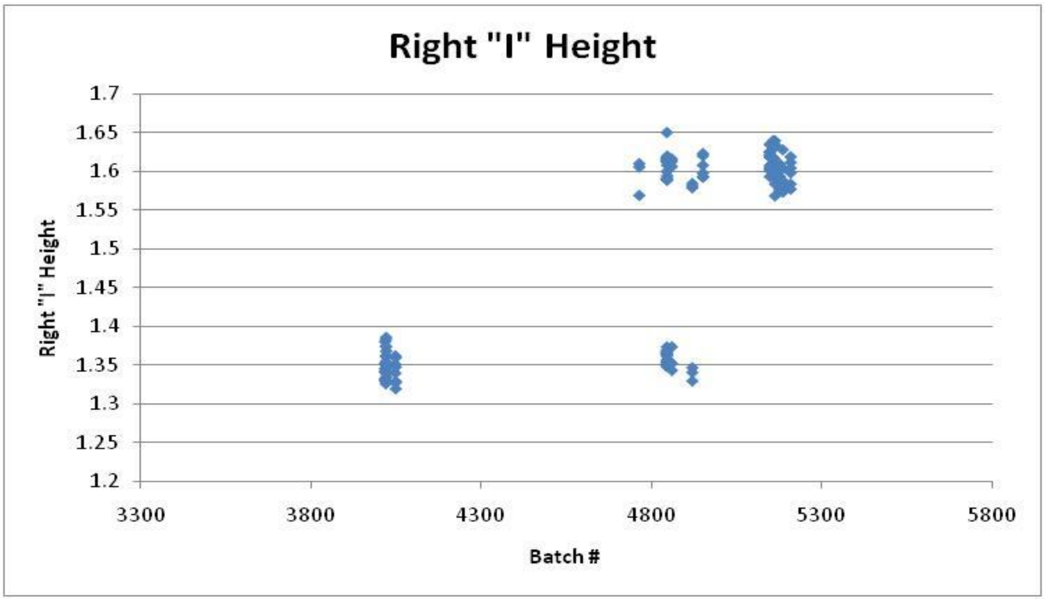

16y
1.4
1.2
1
0.8
0.6
0.4
0.2
0
16y
3300 3500 3700 3900 4100 4300 4500 4700 4900 5100 5300
Batch #

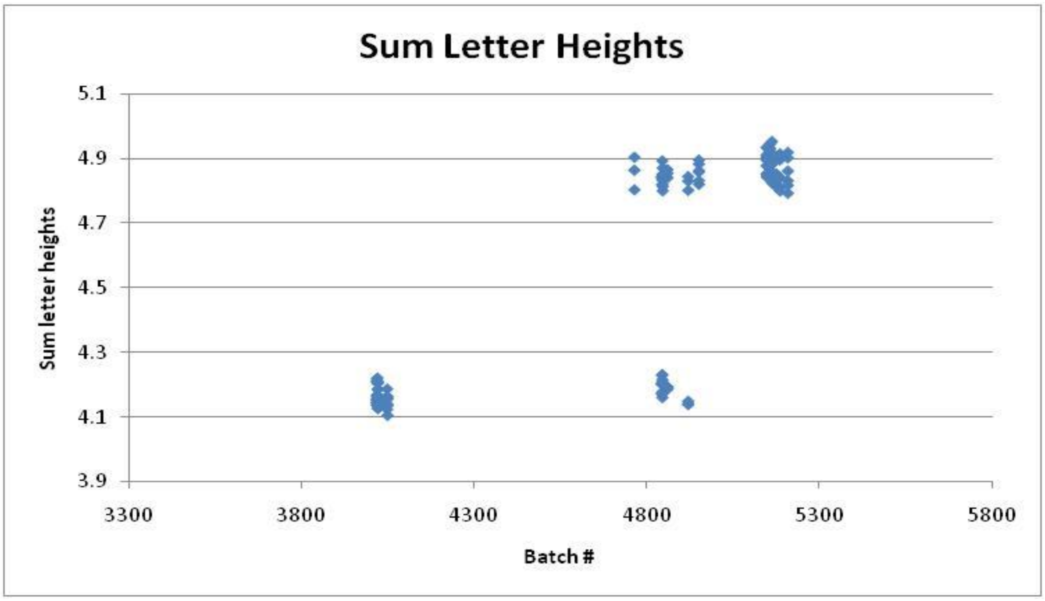
APPENDIX IV

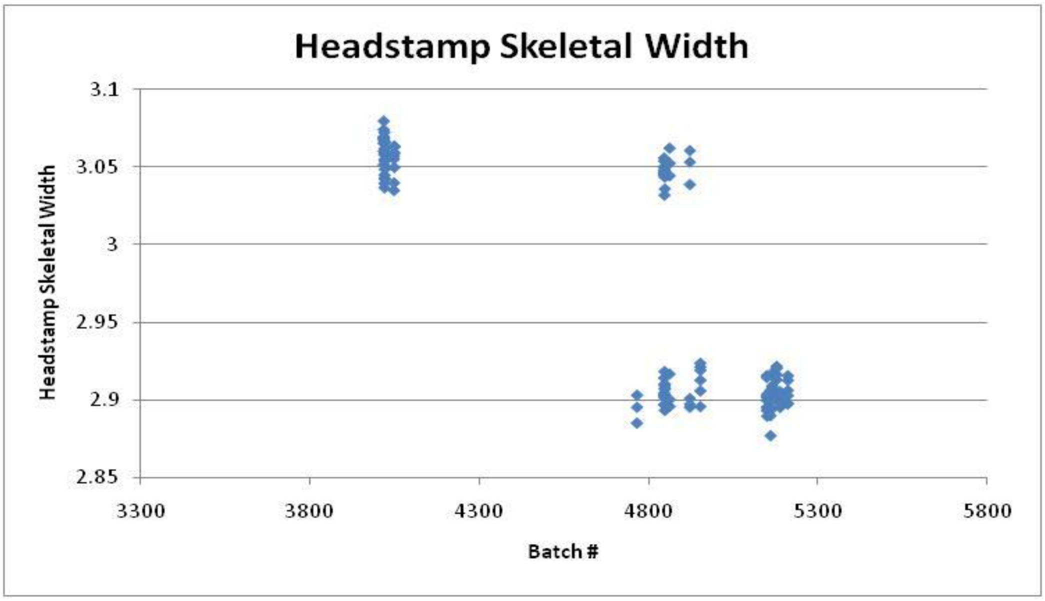
Following are the graphs for each data transformation versus batch number for the wet-primed cartridges. Graphs have also been included for some of the standardised coordinates and diameters of the heads of the cartridges across the vertical and horizontal planes.

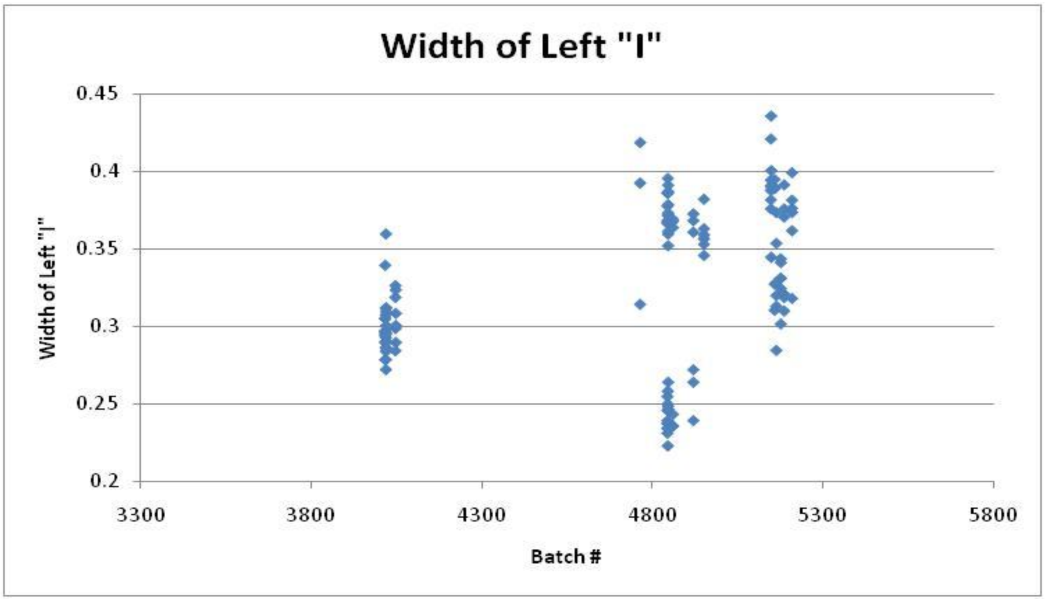




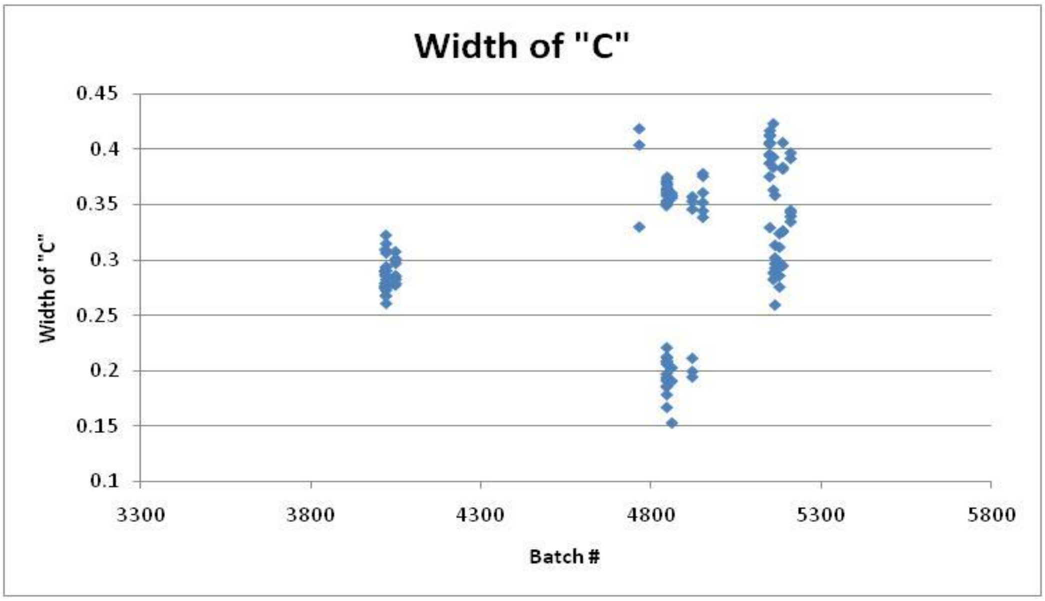

Right "I" Height
Right "I" Height
1.7
1.65
1.6
1.55
1.5
1.45
1.4
1.35
1.3
1.25
1.2
3300
3800
4300
4800
5300
5800
Batch #


Sum Letter Heights
Sum letter heights
5.1
4.9
4.7
4.5
4.3
4.1
3.9
3300
3800
4300
4800
5300
5800
Batch #

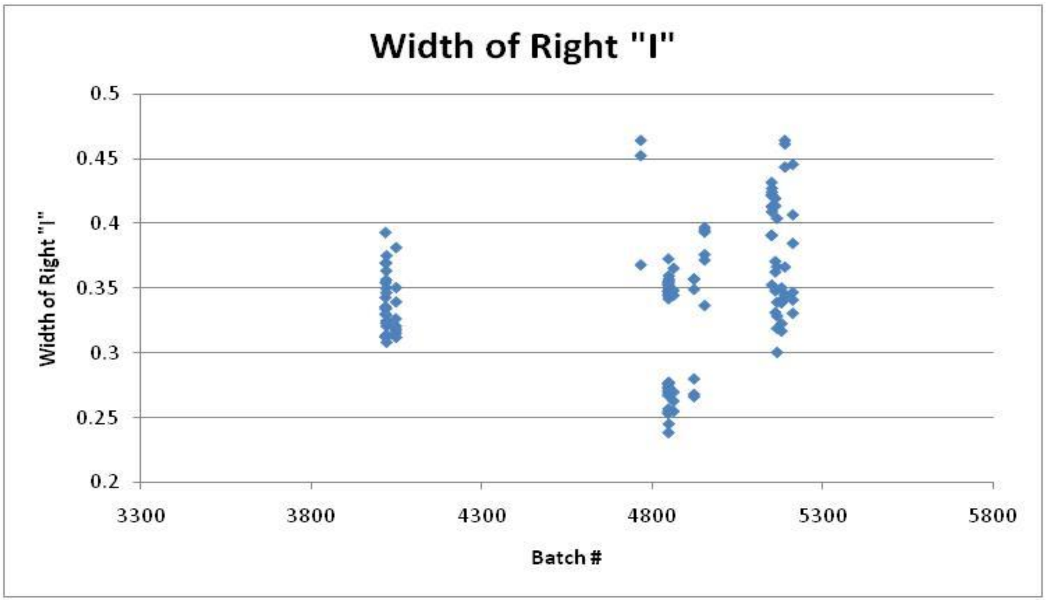

Headstamp Skeletal Width
Headstamp Skeletal Width
3.1
3.05
3
2.95
2.9
2.85
3300
3800
4300
4800
5300
5800
Batch #



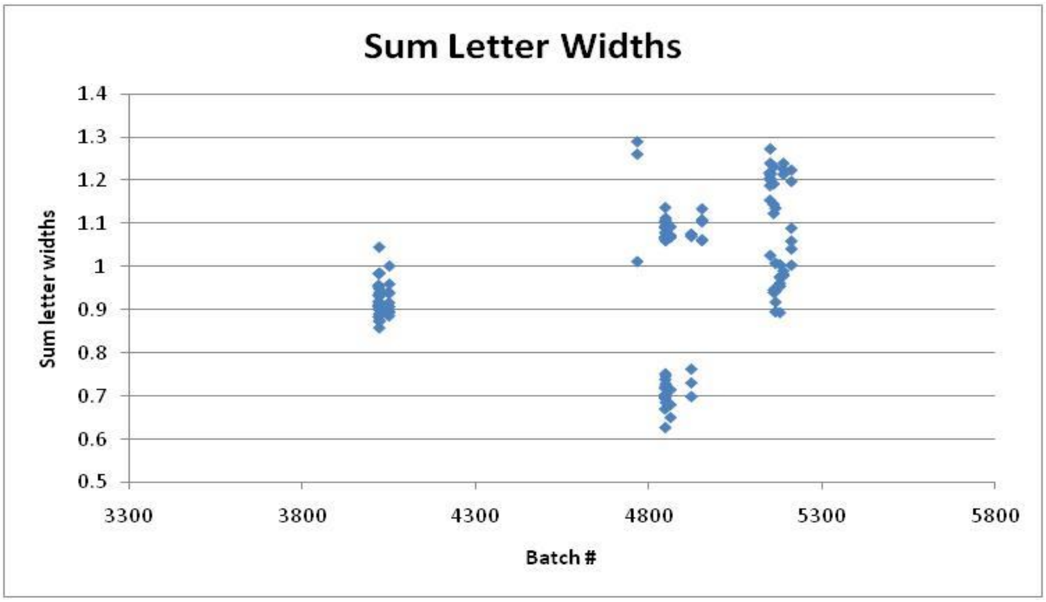
Width of Left "I"
Width of Left "I"
0.45
0.4
0.35
0.3
0.25
0.2
3300
3800
4300
4800
5300
5800
Batch #

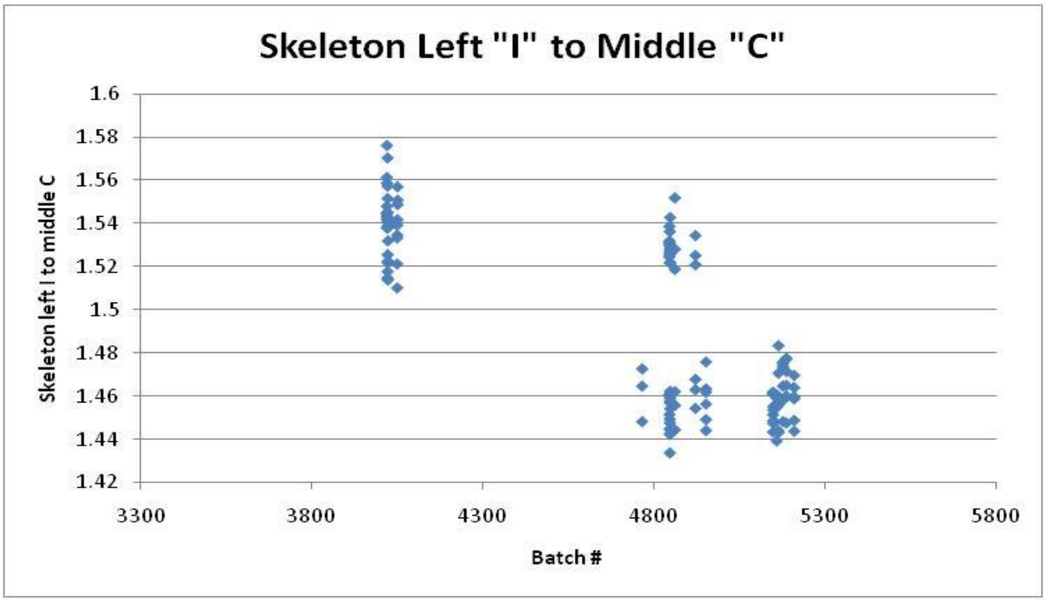


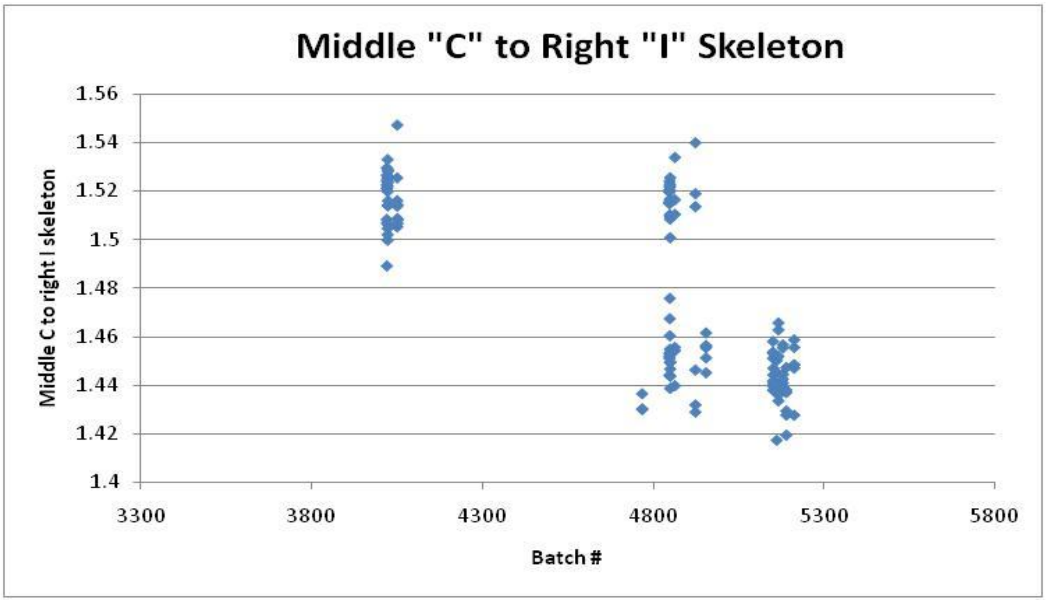
Width of "C"
Width of "C"
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
3300
3800
4300
4800
5300
5800
Batch #

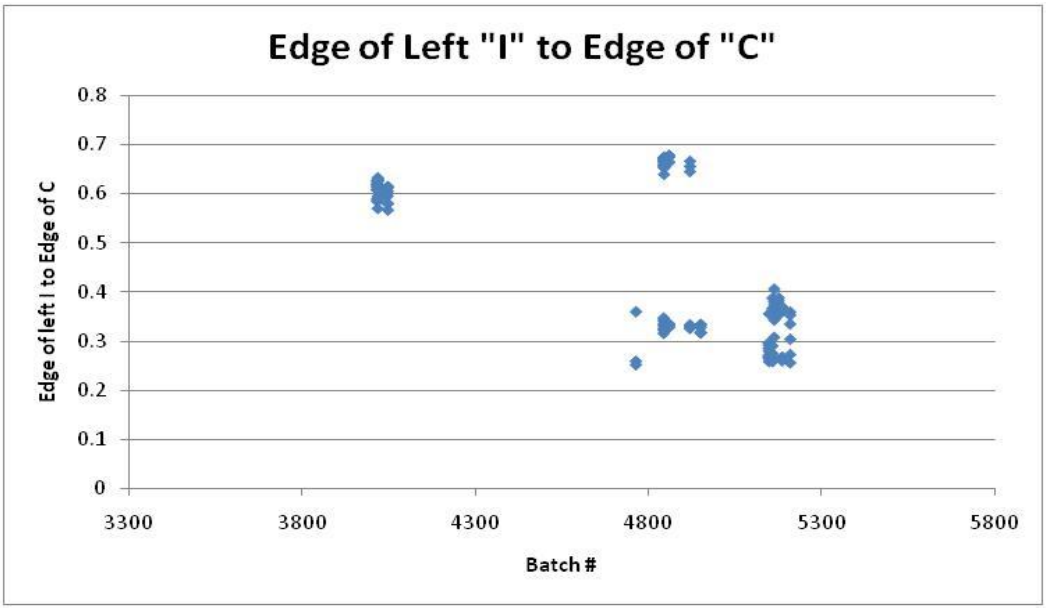


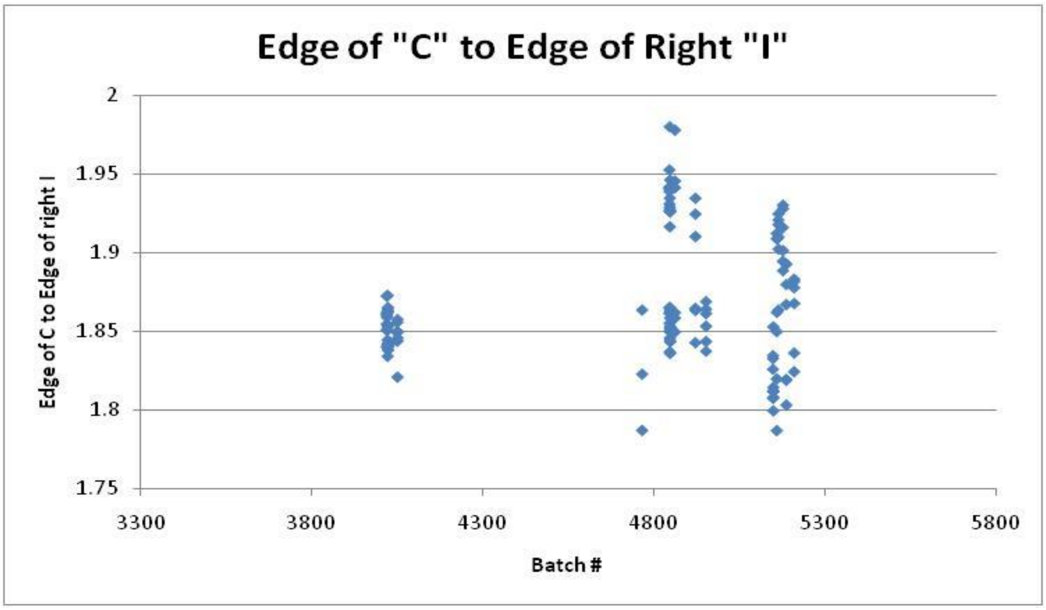
Width of Right "I"
Width of Right "I"
0.5
0.45
0.4
0.35
0.3
0.25
0.2
3300
3800
4300
4800
5300
5800
Batch #

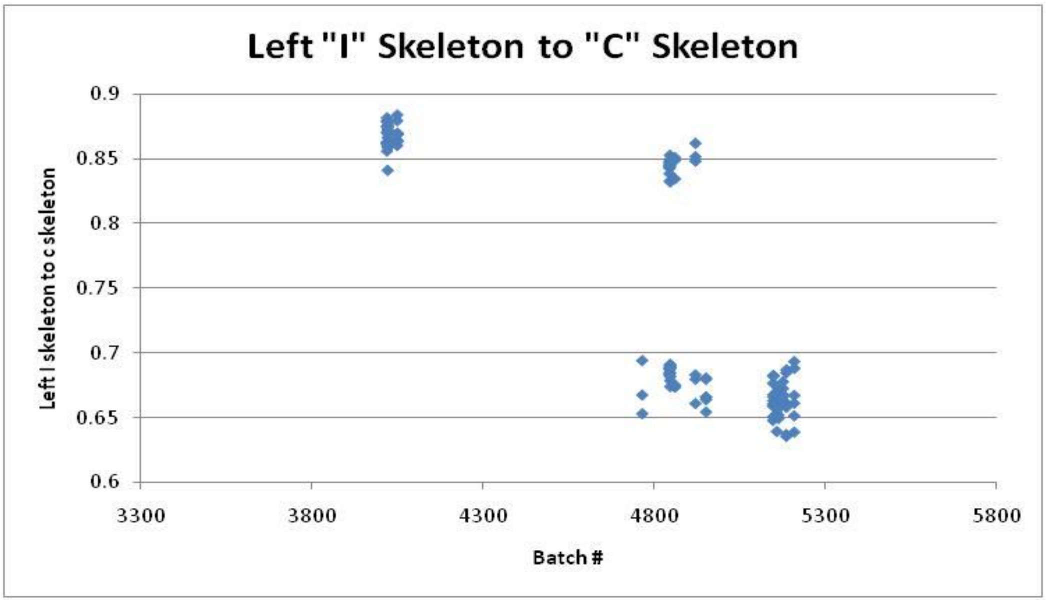

Sum Letter Widths
Sum letter widths
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
3300
3800
4300
4800
5300
5800
Batch #

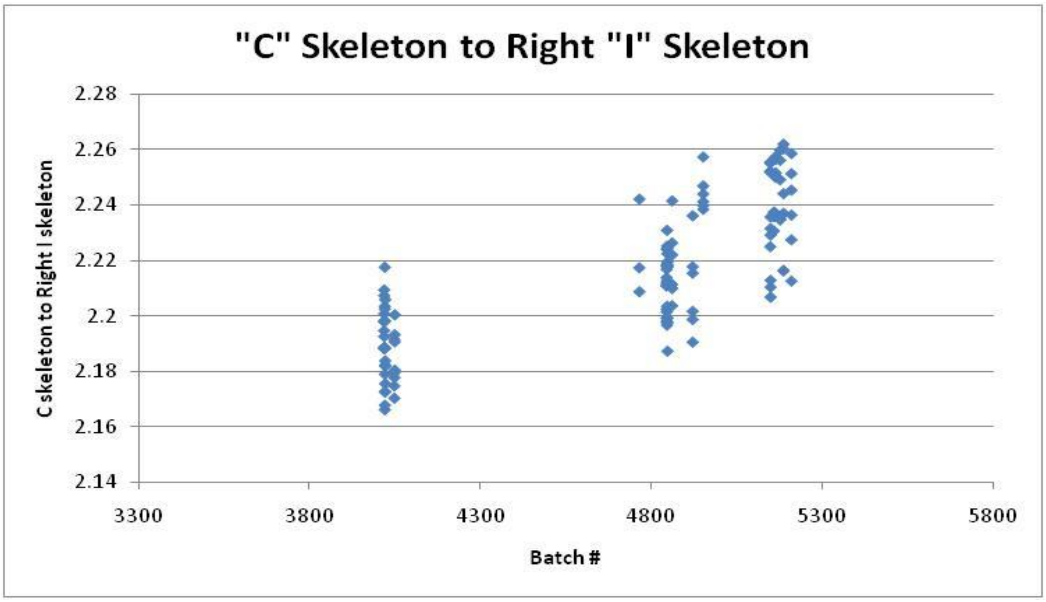

Skeleton Left "I" to Middle "C"
Skeleton left I to middle C
1.6
1.58
1.56
1.54
1.52
1.5
1.48
1.46
1.44
1.42
3300
3800
4300
4800
5300
5800
Batch #

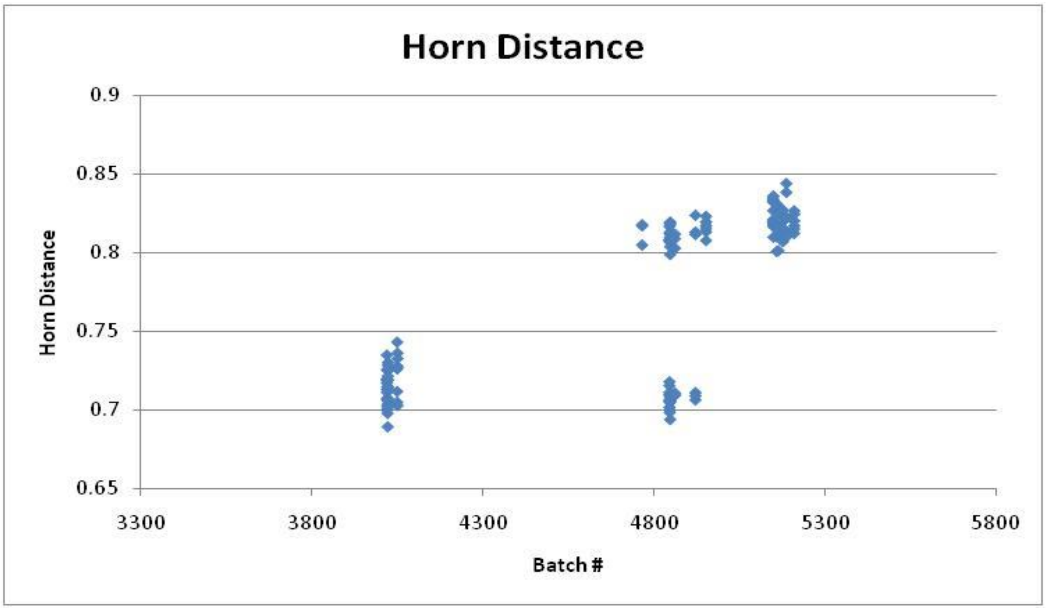

Middle "C" to Right "I" Skeleton
Middle C to right I skeleton
1.56
1.54
1.52
1.5
1.48
1.46
1.44
1.42
1.4
3300
3800
4300
4800
5300
5800
Batch #

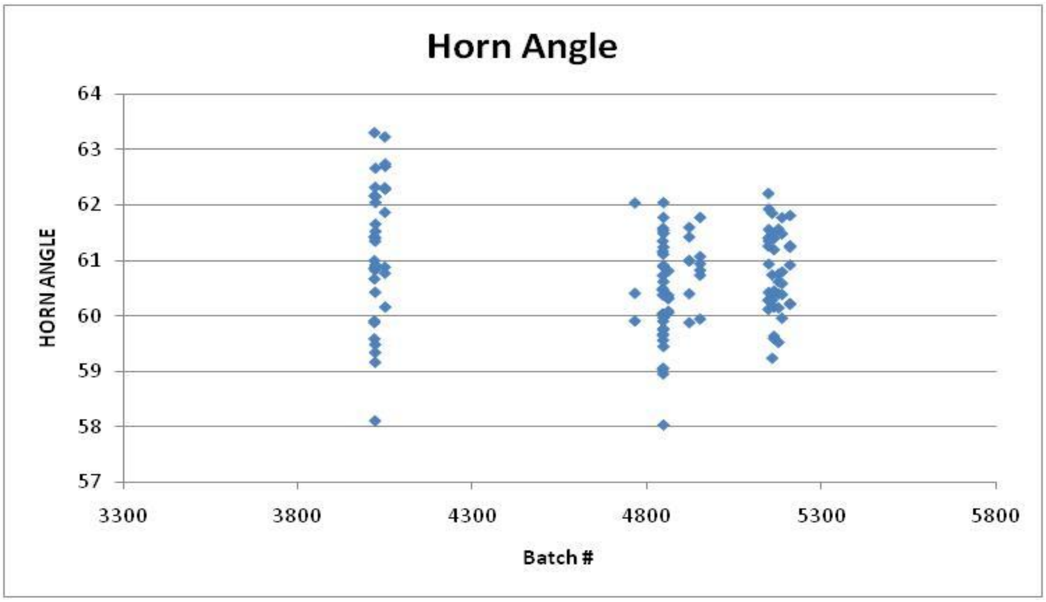

Edge of Left "I" to Edge of "C"
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Edge of left I to Edge of C
3300
3800
4300
4800
5300
5800
Batch #

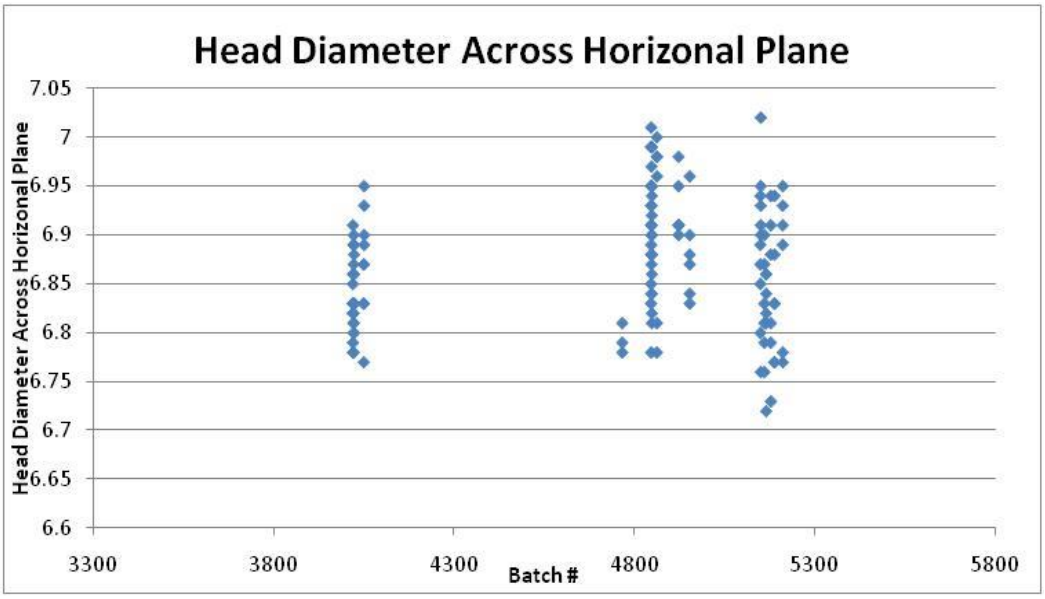

Edge of "C" to Edge of Right "I"
2
1.95
1.9
1.85
1.8
1.75
Edge of C to Edge of right I
3300
3800
4300
4800
5300
5800
Batch #

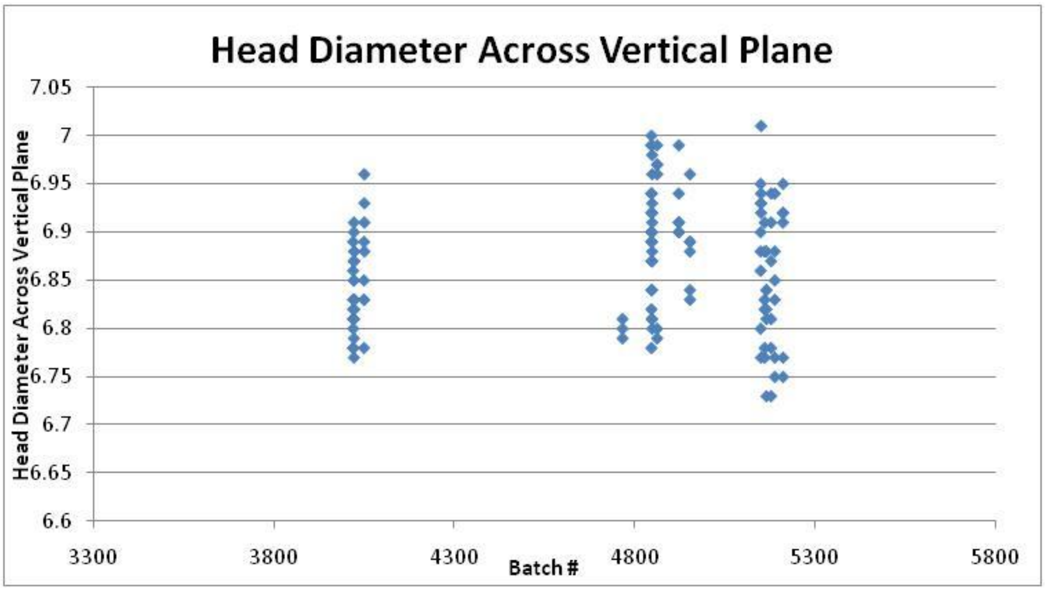

Left "I" Skeleton to "C" Skeleton
0.9
0.85
0.8
0.75
0.7
0.65
0.6
Left I skeleton to c skeleton
3300
3800
4300
4800
5300
5800
Batch #

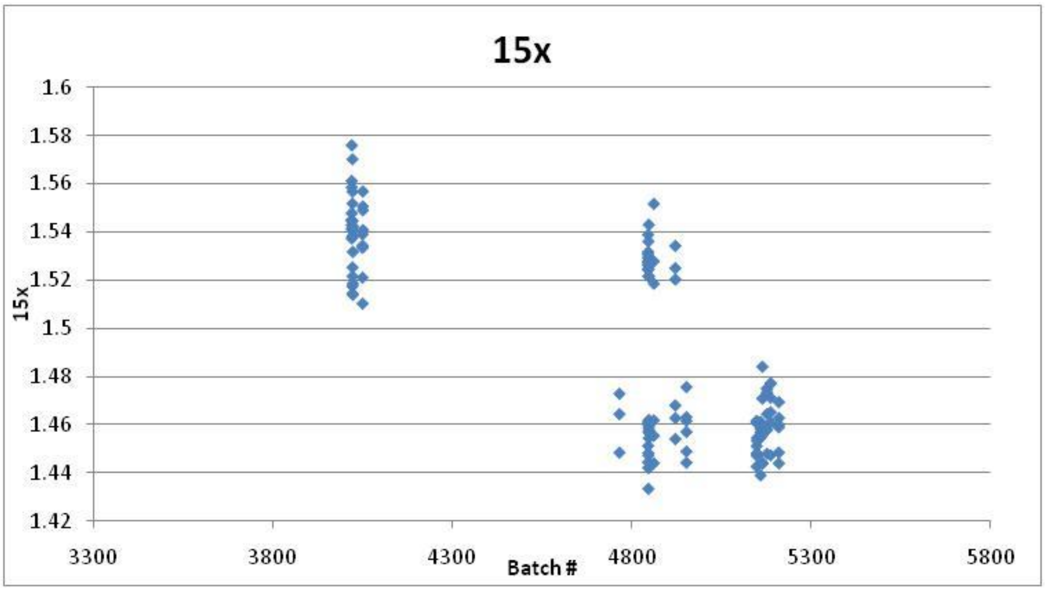

"C" Skeleton to Right "I" Skeleton
C skeleton to Right I skeleton
2.28
2.26
2.24
2.22
2.2
2.18
2.16
2.14
3300
3800
4300
4800
5300
5800
Batch #

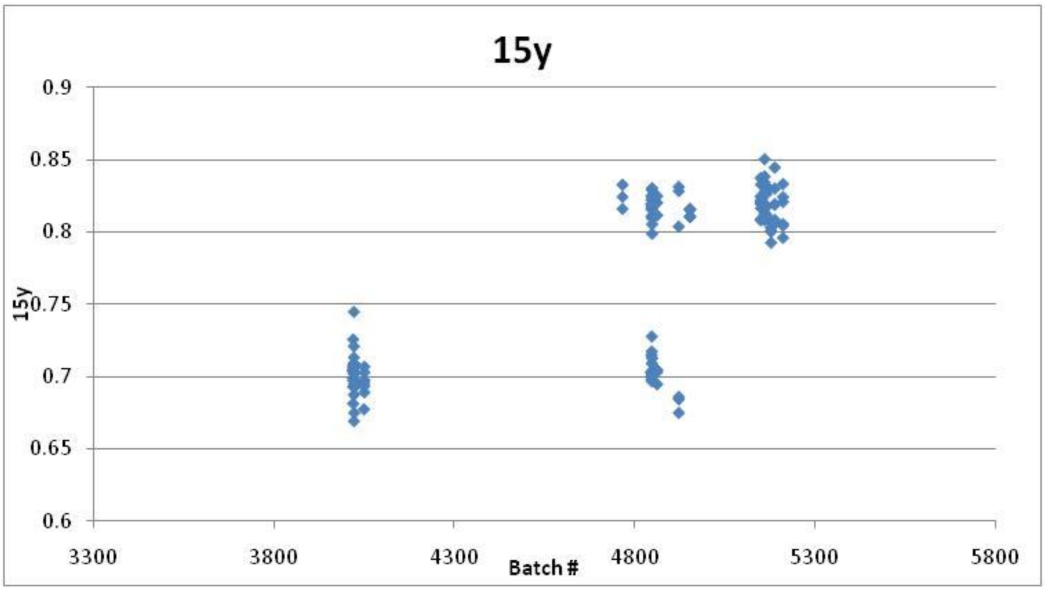

Horn Distance
Horn Distance
0.9
0.85
0.8
0.75
0.7
0.65
3300
3800
4300
4800
5300
5800
Batch #

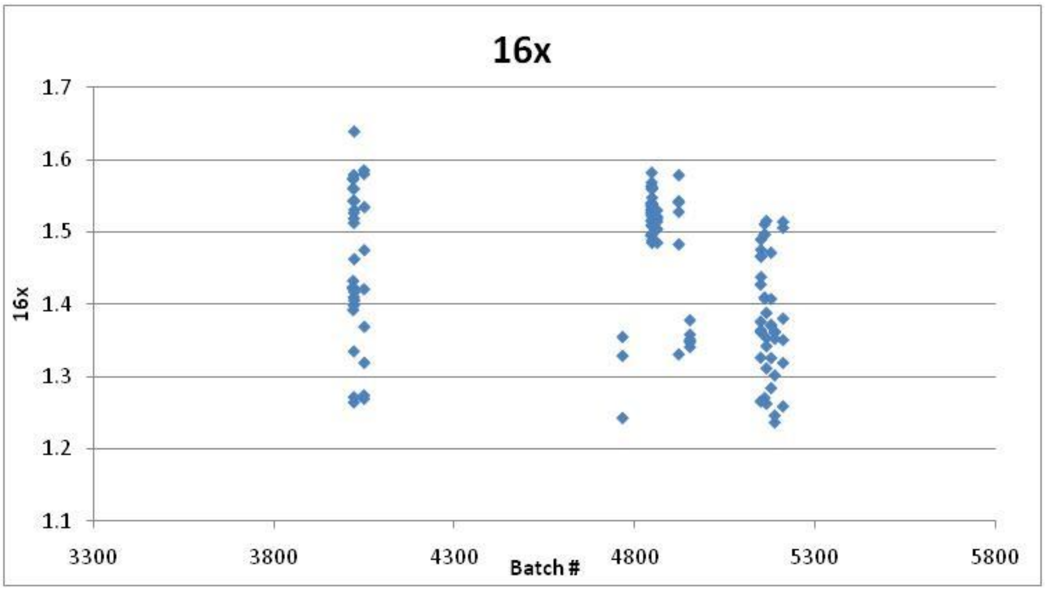

Horn Angle
HORN ANGLE
64
63
62
61
60
59
58
57
3300
3800
4300
4800
5300
5800
Batch #

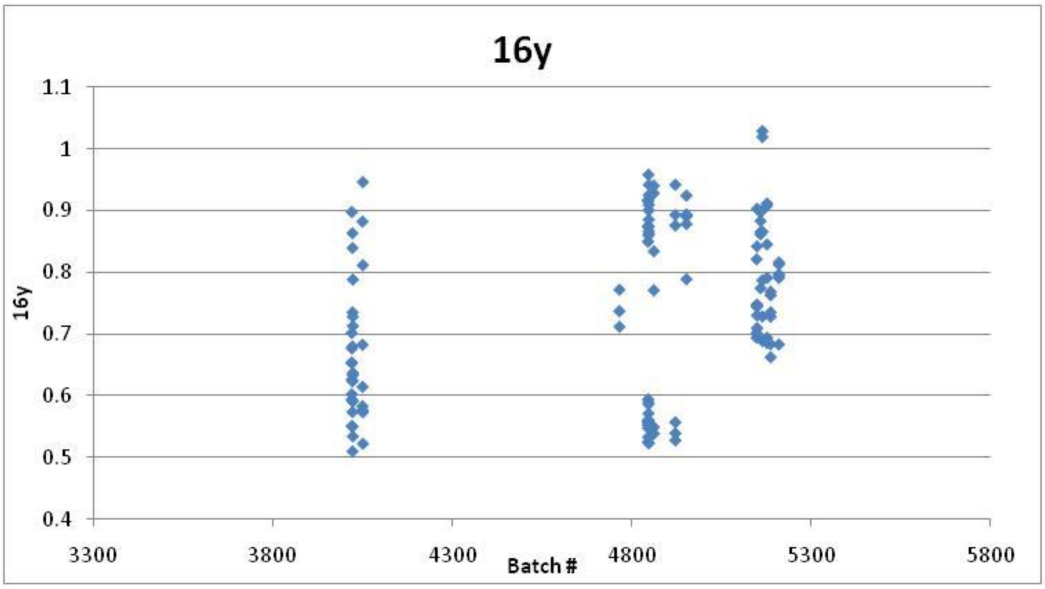

Head Diameter Across Horizonal Plane
Head Diameter Across Horizonal Plane
7.05
7
6.95
6.9
6.85
6.8
6.75
6.7
6.65
6.6
3300
3800
4300
4800
5300
5800
Batch #


Head Diameter Across Vertical Plane
Head Diameter Across Vertical Plane
7.05
7
6.95
6.9
6.85
6.8
6.75
6.7
6.65
6.6
3300
3800
4300
4800
5300
5800
Batch #


15x
15x
1.6
1.58
1.56
1.54
1.52
1.5
1.48
1.46
1.44
1.42
3300
3800
4300
4800
5300
5800
Batch #


15y
0.9
0.85
0.8
0.75
0.7
0.65
0.6
15y
3300
3800
4300
4800
5300
5800
Batch #


16x
1.7
1.6
1.5
1.4
1.3
1.2
1.1
16x
3300
3800
4300
4800
5300
5800
Batch #


16y
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
16y
3300
3800
4300
4800
5300
5800
Batch #

APPENDIX V

Appendix V is stored on a CD that is located at the back of this thesis. It contains raw data, scripts which were used for analysis in R and results for the following:

- Standardised coordinate data for all of the sampled headstamps.
- Transformed data for all of the headstamps.
- The dry-primed data which was used in the statistical analysis in this project.
- The wet-primed data which was used in the statistical analysis in this project.
- The standardised coordinate data and transformations from the blind study cartridges.
- The standardised coordinate data and transformations from exhibit 350.
- An R script for performing Principal Components Analysis, Hierarchical Clustering Analysis and cross-validation with Linear Discriminate Analysis.
- An R script for performing classifications using LDA (with loops for obtaining the number of correct classifications and the average prediction error)
- A full prediction table for cross-validation of the dry-primed data.
- An R script for performing the Block analysis.

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