Five iron nails from the Roman hoard at Inchtuthil

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Introduction

In May 2012 Mr Derek Abbott presented five iron nails from the site of Inchtuthil in Perthshire, Scotland, to the Australian National University Classics Museum. Inchtuthil is famous for an archaeological discovery in 1959 of hundreds of thousands of iron nails buried in a deep pit at the site of an early Roman fortress.

Before putting Mr Abbott's group of nails (the Abbott group) on public display, the museum commissioned the author to arrange conservation, and to research the nails' provenance and manufacture in order to provide evidence-based interpretation of the objects for museum visitors.

The interpretation of the Abbott group has two aspects. The first relates to the group as a distinct collection of artefacts with its own unique story, including how it came to be in Mr Abbott's possession, the state of corrosion of individual objects, and the conservation needed to safeguard the objects for the future. The second relates to the nails as parts of a broader material culture, where the technical information gleaned about iron manufacture, technology and practice can help to increase our understanding of the archaeology of Roman Britain.

This report starts with an account of the known historical background of Inchtuthil nails, pieced together from primary and secondary sources, and the anecdotal information associated with the Abbott group. We look at the physical properties of the group, particularly the relationships between deposition and corrosion, and details of the work necessary to conserve and prepare the nails for exhibition. Following this, the paper explores how the nails may have been made, based on other examples from Inchtuthil, and the significance of this information in helping to interpret the past.

Historical setting

The Abbott group is connected to the famous excavations at the Roman legionary fortress at Inchtuthil (also Inchtuthill) on the north bank of the Tay in Perthshire, Scotland. In the 1950s and 1960s, Professor Ian A. Richmond and Dr. J. K. St Joseph uncovered the foundations of a Roman fortress at Inchtuthil, built in AD 83 as the advance headquarters of Agricola. [1, 2]

After a few years of occupation, the site was abandoned sometime between AD 86 and 90, purportedly when the legion (Legio XX Valeria Victrix) was withdrawn from Scotland. The Roman frontier fell back south leaving the fortress well inside the territory of the Caledonian tribes. Before retreating, the legionaries dismantled and destroyed the fortress, demolishing and burning buildings, smashing pottery, and filling in drains and sewers to ensure nothing of use or assistance to the enemy was left behind. Unable or unwilling to transport the huge stockpile of unused iron nails in the workshop (fabrica) of the fortress, the Romans dug a 4-metre deep pit in the corner of the workshop, buried the iron and then removed the superstructure. There would have been little outward trace that the legion's workshop once stood erect, let alone evidence of the valuable iron stock buried deeply. In 1959 Richmond and his team trenched across this part of the site and dug down, Richmond famously being tipped off by a change in the soil colour to investigate further. The excavators came across a hoard of iron nails, comprising over 875 000 individual objects and weighing about seven tonnes. [2] (Figure 1)

Figure 1: Photograph of nails excavated at Inchtuthil, 1959. ©Royal Commission on the Ancient and Historical Monuments of Scotland (000-299-998-257-R).
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Richmond sent the hoard to the National Museum of Antiquities of Scotland in Edinburgh. The museum, in turn, contacted the Iron and Steel Institute, and the finds were transferred to the Dalzell Steel and Iron Works of David Colville & Sons (Colvilles), a Scottish iron and steel company in Motherwell, southeast of Glasgow. Colvilles sorted through the hoard, freeing individual items where they were fused. The company tallied an unusually large collection from the Roman period: 763 840 small nails, 85 128 medium nails, 25 088 large fasteners and 1344 extra large spikes "16 inches long". [3]

A number of the workers at Colvilles were former students of Mr Abbott's aunt, Mabel Cameron MBE. Knowing she was a keen amateur archaeologist, they liberated several of the nails and presented them to her in a wooden box. Ms Cameron kept the box in the back of a drawer for many years. The box was then passed to Mr Abbott, who brought it to Canberra in the 1980s and stored it, variously, in a bookshelf, drawer, and the garage under the house. (Derek Abbott, personal communication.) He presented the box to the Australian National University Classics Museum in May 2012. The box was accompanied by a copy of an article in Colvilles Magazine about the nail hoard and a facsimile of a photograph of the five items, presumably before they were boxed. (Figure 2)

Figure 2: Photocopy image (author unknown) of the Abbott nails circa 1960; clockwise, starting with largest nail, is A1, A2, A3, A4 and A5

Physical description of the Abbott group

The Abbott group comprises one large nail (A1), two medium-sized nails (A2 and A3) and two small nails (A4 and A5). (Table 1) All the nails are square-sectioned along the entire length of a tapering shank forming a four-sided tapered point (also called a diamond point). The head of nail A1 has been formed into a rough pyramid, known in blacksmithing terminology as a rosehead. Nails A2, A3, A4 and A5 have flat, disk-like heads and in all cases the head is eccentric in relation to the shank.

Previous research on the Inchtuthil nails includes a nail typology published by Angus, Brown and Cleere. [4] Angus et al. divided the Inchuthil nails into six main groups based on head type (pyramidal or flat head disk), length, and dimensions of the die used for forming the head (determined by measuring the section of the shank below the head). The five Abbott nails (referenced A1- A5 in this paper) are typologically consistent with the classifications of Angus et al. as follows:

Nail A1 is compatible with Angus et al.'s Group A(i) – large nails characterised by their length and pyramidal head. The head of A1 has an approximate apex angle of 120 degrees however the profile of the head is not symmetrical.

Nails A2 – A5 are compatible with Angus et al.'s Groups B and D – standard Roman nails with a flat disk head of widely variable size, often eccentric to the shank.

Abbott nail	*Angus, Brown and Cleere [4]*	*Head*	*Length (cm)*	*Dimensions of shank section below head (cm^2)*	*Weight (g)*	*Density* (g/cm^3)*
A1	Group A(i)	pyramidal	26.0	1.56	212.5	7.33
A2	Group B	flat disk	19.0	0.81	46.7	6.23
A3	Group B	flat disk	17.5	0.81	37.3	7.46
A4	Group D	flat disk	6.3	0.25	8.9	7.42
A5	Group D	flat disk	6.4	0.09	3.0	6.00

Table 1: Comparative density, size and weight of the Abbott collection nails, prior to conservation

*Note, for comparison, uncorroded plain low carbon steel (less than 0.15 per cent carbon) has a density of 7.85 g/cm^3.

When presented to the museum, nails A2 and A3 were each secured with a thin 8 mm-wide copper alloy clip near the head and a steel staple coated with alkyd resin at the point. The large iron nail (A1) was unsecured. Mr Abbott explained that nail A1 had worked itself loose over the years but that it too had once been held in place with a staple at the point and a copper clip at the head. (Derek Abbott, personal communication) This is corroborated by fastening-holes in the plywood base. (Figures 4 and 6) Nails A4 and A5 were secured with only the resin-coated steel staples. However, part of nail A4's head was deliberately embedded into a recess in the plywood base. (Figure 5)

Figure 3: Boxed set of Abbott group prior to removal

The items were presented in a hardwood box with a plywood base and covered with a clear plastic lid. (Figure 3) A printed plastic label provides some interpretation of the showcase and reads as follows: *Iron nails from Roman legionary fortress at Inchtuthil, Perthshire, Scotland AD 83-87.*

Figure 4: Nail A2 (bottom) with copper alloy clip and the point of nail A1 (top) beside holes in the plywood base

Figure 5: View of head of nail A4 embedded into plywood base

All the nails have signs of corrosion such as loss of density, shape distortion, pitting, flaking and varied surface colouring. Nail A1's point has a visible loss of material approximately 20 mm from the tip and a thin layer of white adherent matter around this area. (Figures 4 and 6) Nail A4 has a visible loss of material at the part of the head that had not been embedded into the plywood base. (Figure 5) Nails A2 and A5 have thin and jagged heads, with a visible loss of material at the head of both nails.

Figure 6: View of nail A1 showing loss of material and white adherent, approximately 20 mm from point (magnification 6x)

Compared to the other nails, the shank areas below the heads of nails A2 and A3 show signs of significant cracking and flaking of the oxide matrix. Nail A3 has a series of fissures about 25 mm from the head associated with red and glassy brown corrosion products. (Figures 7, 8 and 9)

Corrosion and mechanical damage

An important aspect of the Inchtuthil iron hoard find was the good state of preservation of many of the nails when they were excavated in the late 1950s. From the accounts, Richmond dug down several metres and came upon a solid crust of fused, rusted iron, which covered an inner core of iron nails in surprisingly good condition. [3] A reaction had taken place between the outer nails and oxygen in the groundwater to form an oxide crust but by the time water diffused into the interior of the mass, it was less corrosive. The crusted outer nails had not only acted as a hydraulic barrier but, combined with their consumption of oxygen, caused anaerobic conditions around the innermost nails. [5, 6]

The image of the Abbott group in the photocopy circa 1960 (Figure 2) shows the nails to be in good form and comparatively intact, without signs of significant flaking and cracks or other mechanical damage. The condition of the Abbott group nails in the photocopy is consistent with the reports of the condition of most of the Inchtuthil nails when they were exhumed. This is in contrast to the current state of the objects as described above. (Figures 3–6) The difference in appearance suggests that the nails have continued to corrode in the 50 years since they were recovered from the pit in Scotland, and that they have been damaged mechanically. In this section we explore the likely reasons for this.

Figure 7: Nail A3 (middle object) prior to removal

Analysis of corrosion products

The current appearance of the nails (pitting, cracking, discolouration and flaking) is largely the result of the formation of iron oxides, which occurs when untreated iron is exposed to an oxygen-rich environment.

Iron corrosion is essentially an electrochemical process involving oxidation and reduction reactions. During burial, archaeological iron reacts with oxygen and moisture in the soil. An anodic reaction takes place at the surface of the iron, that is, solid iron loses electrons and is oxidised, forming iron(II) ions ($Fe \rightarrow Fe^{2+} + 2e^-$). Meanwhile a countering cathodic reaction takes place involving the reduction of oxygen with water to form hydroxide ($O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$). At the surface, iron(II) ions (Fe^{2+}) dissolve, accumulate and solid iron(II) hydroxide ($Fe(OH)_2$) precipitates. Further oxidation of iron(II) hydroxide ($Fe(OH)_2$) forms iron(III) hydroxide ($Fe(OH)_3$) or iron(III) oxyhydroxide (FeOOH). Iron(II) and iron(III) ions are able to form continuously at the interface between solid metal and corrosion products, with the ions dissolving, accumulating and undergoing hydrolysis. The ions are positively charged (cations) and attract negatively charged ions (anions) such as chloride (Cl^-).

Post burial, iron is exposed to an environment of comparatively lower relative humidity and higher oxygen concentration than when it was buried. [7] It dries rapidly and the corrosion layers crack, flake and distort the shape of the object. Fissures, cracks and pits expose fresh layers at a lower oxidation state, such as magnetite (Fe_3O_4), to the corrosive conditions. The corrosion process continues until all metal is exhausted or unless the corrosive conditions cease.

Typically, ancient iron objects are made up of layers of corrosion product that are at various states of iron oxidation. The outer layer often contains products at a high state of oxidation such as goethite (α-FeOOH) and lepidocrocite (γ-FeOOH). [8, 9,10] Using a Raman microspectrometer (633 nm radiation laser), we analysed samples from nails A1, A2 and A3 to determine the nature of the corrosion products in preparation for conservation. Nails A1, A2 and A3 were chosen because they had easily removable flakes of oxidised material without requiring more intrusive sampling. There was also an aim to search for the particularities of nails A2 and A3, as these appeared to be comparatively more corroded items. Most of the samples were typically uneven in colour, texture and thickness. The resultant Raman peaks are set out in tabular form in Appendix 1. Selected Raman spectra are presented in Appendix 2. (Cornell and Schwertmann's published Raman reference series for iron oxides is used throughout this paper. [11])

Oxide phases commonly associated with archaeological iron are goethite, lepidocrocite and magnetite. These oxide forms were detected, although few samples produced results convincingly consistent with the Raman peaks for magnetite (approximately 667 cm^{-1}). The paucity of magnetite results could be explained by the fact that we focused on flaking samples and highly fissured areas of the objects, which are more likely to yield iron corrosion product at a high state of oxidation. Notably, a number of the samples produced results consistent with Raman peaks for akageneite (β-FeOOH). (Appendix 1)

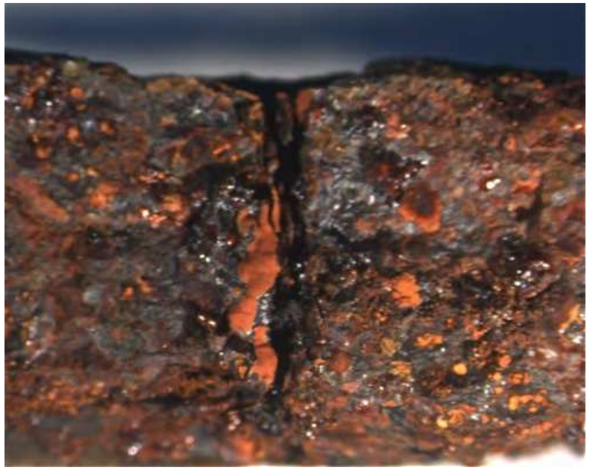


Figure 8: Nail A3 showing fissure approximately 25 mm from head (magnification 6x)

In relation to nail A3, a focus was the large fissure approximately 25 mm from the head. (Figures 8 and 9) Samples were taken from inside and around the fissure, that is, samples of the red oxide product as well as the contiguous glassy brown product. The red oxide product was friable and granular; the glassy brown product was highly friable and broke up on contact into a powdery yellow mass of tiny spindle-like crystals. We tested samples in glassy brown as well as powdery yellow form. (Appendix 1: Samples 22 - 26; Appendix 2: Sample 23) Results for both products were consistent with Raman peaks for akageneite. Results from the red oxide product were consistent with Raman peaks for haematite, goethite and akageneite.

Akageneite is a product that forms in the corrosion layer of iron, causing significant mechanical damage. [7] It forms on archaeological iron after excavation and the presence of akageneite is evidence that the object is contaminated with chloride. [12] As mentioned earlier, during burial, positively charged iron ions attract negatively charged ions, such as chloride ions. Post excavation, the chloride ions act as corrosion accelerators once the iron objects are exposed to oxygenated atmospheres at as little as 15 per cent relative humidity. [13]

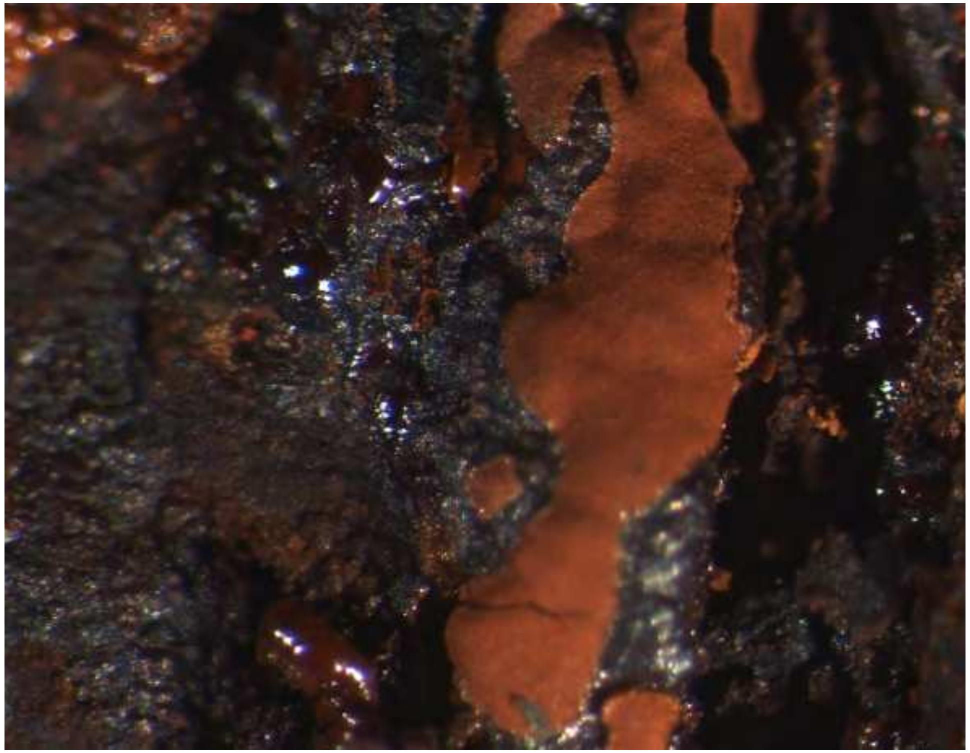


Figure 9: Nail A3 red oxide and glassy brown corrosion product in and around fissure (magnification 25x)

In addition, we investigated further the areas of nails A2 and A3 that were in contact with the copper alloy clips. (Figures 4 and 7) In theory, because of the direct contact of dissimilar metals, galvanic coupling may have accelerated corrosion in localised areas under the heads of nails A2 and A3. There were reddish brown deposits on the copper alloy clip used on nail A2 visible at the macroscale. (Figure 10)

Figure 10: Deposits on the surface of the copper alloy clip in contact with nail A2 (magnification 40x)

Analysing the deposits with the Raman microspectrometer (785 nm radiation laser), we found the results were consistent with Raman peaks for goethite (α-FeOOH). (Appendix 3: Graph 1). There is an electrode potential difference between iron and copper, the potential of iron being lower. In an iron-copper system, iron acts anodically and dissolves in the presence of an electrolyte (for example, moisture inside the box), giving up electrons to the cathode (copper). The presence of iron oxide corrosion deposits on the surface of the copper alloy clip indicates that galvanic corrosion had occurred in localised areas in contact with copper.

One final source of corrosion acceleration may have been the small, closed wooden showcase itself. Wooden storage and display units can emit high concentrations of volatile acetic acid vapour when wood cellulose is broken down by moisture into acetic acid. Acid vapour has a deleterious effect on metal artefacts and acts as a corrosion catalyst. [14,15] Depending on ambient air temperature, moisture is released from the wood into the poorly-ventilated space of an enclosed box resulting in high relative humidity. Moisture contributes to the formation of the organic acid vapour and facilitates corrosion.

We took readings of the environment inside and outside the box and found that while the box acted as an environmental buffer, the relative humidity inside the box ranged from 58.7 per cent to 60 per cent over four days of testing. (Appendix 4: Graph 1) Relative humidity levels below 35 per cent are needed to reduce the rate of corrosion of iron significantly. [16] Further experiments could be undertaken on the wooden box to examine the concentrations of acetic acid vapour emissions possible under controlled environmental conditions.

Mechanical damage

It was suspected that the loss of material and white adherent at the point of nail A1 were related to the coating on the remnant steel staples. We took a sample of white adherent at the point of nail A1. (Figure 6) The sample was analysed with fourier transform infrared microspectroscopy and the results were most consistent with references for calcium carbonate ($CaCO_3$). (Appendix 5: Graph 1) XRF results confirmed that the white adherent on nail A1 was a calcium cation. (Appendix 3: Graph 2) We also tested the steel staples and confirmed that they were coated with alkyd paints by showing characteristic alkyd resin peaks (approximately 1730 and 1280 cm^{-1}). (Appendix 5: Graphs 2 - 3) Alkyd paints are used to inhibit corrosion in modern steels and notably some alkyd paint products contain precipitate $CaCO_3$ as an extender. A reasonable conclusion is that the adherent on the point area of nail A1 comprises $CaCO_3$ from the resin coating on the staple. That is, the evidence suggests that clamping this particular nail with steel staples caused abrasion and loss of material to the point of nail A1 and a transfer of material from the staples to the iron.

In relation to nail A4, which had part of its head embedded in the plywood base, the form of the exposed part of the head has the appearance of a breakage. (Figure 5) It looks as if this damage occurred after the image in Figure 2 was taken. (In Figure 2, nail A4 is the second nail from the top.) It was suspected that damage to the head is related to impact blows caused by forcing the head into the plywood base, presumably with a hammer. However, it was not possible to take a longitudinal section sample of the head of nail A4 for metallographic analysis without damaging its current shape and appearance irrevocably. We were, therefore, unable to test this theory.

Earlier, we noted that Colvilles had liberated and subsequently boxed the items in the late 1950s to early 1960s. There is no evidence to suggest that the objects had been desalinated or treated, although they may have undergone some mechanical cleaning to separate objects if they were fused or to remove dirt and stones. We now know that there are likely to be several reasons for appearance of the objects: atmospheric corrosion of the iron and damaging mounting practices to hold and display the objects.

Figure 11: Prising out the steel fasteners on nail A4; staple holes were widened with a power drill to reduce the risk of friction damage on the nail

Treatment

Treatment options and the treatment methodology are set out in this section.

Options

We considered several options to mitigate chloride contamination of the objects. [17,18] The extraction methods, while effective in reducing the levels of chloride, require comparatively long treatment times and do not guarantee total extraction of chloride. These were not suitable for this group in the circumstances. Electrolysis was also considered as a method for desalination. [19] However, parts of some of the nails were too thin and fragile to undergo electrolysis. This method was not preferred.

We considered passivating the iron with a chemical treatment that would turn the mix of unstable iron oxides into a stable corrosion product. In particular, we considered the application of an organic polymer, tannic acid, to react with the iron oxide and convert it to iron tannate, a stable blue-black corrosion product. Disadvantages with this treatment are that it does not eliminate the need for environmental controls, it can stain objects to an undesirable colour if not applied cautiously, and it does not extract chloride or other soluble salts from actively corroding iron. In order to mitigate the risk of ongoing corrosion, the treated objects will need to be stored in a showcase at low relative humidity and will need to be monitored periodically for any spots of rust appearing through the iron tannate film.

Methodology

The first step in conservation was to remove the clips and staples and release the objects carefully from the wooden box. (Figure 11) The surfaces of the iron nails were prepared for treatment by careful mechanical cleaning with steel brushes, scalpels and probes and washing in ethanol (CH_3CH_2OH).

A tannic acid solution (2.5 per cent w/v) was prepared from tannic acid, distilled water and ethanol. We applied numerous thin coats of the solution with acrylic brushes, brushing continuously as the acid dried to help distribute the solution evenly and to remove flaky areas of iron tannate. We continued applying the solution until there was an even and dense film of iron tannate.

A protective microcrystalline wax was applied to the dried nails to act as a vapour barrier. However the objects will need to be stored in a display case with a stable relative humidity at a low level. According to studies of corrosion potential for chloride-containing archaeological iron at different levels of relative humidity, it was found that 12 per cent should be the maximum allowable relative humidity for long term storage and display [13,17] This may not be possible in a mixed display in a small museum, as other objects such as wood, bone and textiles displayed in the same case may be damaged at such low relative humidity. A very low relative humidity could be achieved if the nails are displayed in their own display case, and a conditioned dessicant is placed in the well-sealed case. The objects should not be exposed to acid or other pollutants in display or storage from building products, such as wood, paints, etc. which release acetic and formic acid.

Manufacture of the Inchtuthil nails

In the introduction, we discussed the two aspects of interpreting the Abbott group. We have already focused on the first part by recounting the unique circumstances of the group and undertaking a forensic look at individual objects. The second relates to the nails as parts of a broader material culture and we start this interpretation by looking at what the Inchtuthil nails tell us about iron production and manufacture in the Roman period.

Iron production, manufacturing methods and even some forging techniques can be captured in the chemical composition, thermal and fracture growth history of an iron object. However, these analyses usually require destructive or disfiguring sampling and this is not acceptable for a collection destined for museum presentation. Instead, existing analytical reports of Inchtuthil nails can be used as a reference, assuming the nails analysed previously are representative samples. [4,20]

There are two stages involved in making handmade iron nails: the production of the raw material into stock, which involves sourcing iron ore and fuel and smelting in furnaces, followed by the forging of stock into a finished object in the workshop.

Production stage

Angus et al. [4] found that a number of the nails they analysed displayed two or more contiguous zones of high and low carbon iron especially along the shank. The iron stock used in the manufacture of the Inchtuthil nails was clearly heterogeneous in character. This is typical of iron produced by direct reduction of the iron ore.

Direct reduction, also known as solid-state reduction, was the dominant process for producing iron in Europe up to the Middle Ages. Small, charcoal-fuelled furnaces did not reach temperatures high enough to melt iron (1536 degrees Celsius). Instead such furnaces were able to achieve thermal conditions between 1150 and 1200 degrees Celsius. This was sufficient to reduce iron oxide with carbon monoxide to form iron in a solid state (with entrapped liquid iron silicate known as slag) and carbon dioxide. A simplified representation of the reduction reaction above is: $FeO + CO \rightarrow Fe + CO_2$.

The product of direct reduction of the ore is called a bloom and is a spongy, pasty mass of solid iron with the entrapped liquid slag formed when iron oxide reacts with silica or silicate impurities in the iron ore. While hot, the mass is hammered to express the slag and consolidate the iron. Generally, the particles of iron in the bloom are comparatively low in carbon (pure iron), however particles of higher carbon iron may also be present. This occurs because the zone in which iron reduction takes place in the furnace has to be at a certain distance from the air inlet so as to have a high enough CO/CO_2 ratio to reduce the ore. The reduction zone is actually much cooler than the area immediately around the air inlet and it is where the hard, crystalline alloy iron carbide (Fe_3C or cementite) is produced. Droplets of high-carbon iron fall to the hottest part of the furnace where they are blasted with hot air and oxidised, lowering the carbon content of the metal. [21] But, depending on where they are positioned in the furnace during smelting, the particles may be shielded from the air inlet. The metal particles from these areas would have a comparatively higher carbon content and would be comparatively harder than pure iron. As the bloom is consolidated and formed into rod-shaped stock, particles of higher carbon content are hammered with particles of lower carbon content often in uncontrolled and random ways, resulting in stock that is highly variable in chemical composition, and hardness. [22, 23]

The nails examined by Angus et al. [4] show evidence of heterogeneity typical of direct reduced iron. However, the researchers observed a trend that smaller nails tended to have a low ratio of high-carbon areas while larger nails tended to comprise more extensive zones of higher carbon. This could indicate that there was some material selection, presumably based on a smith's experience of the workability of material.

In the case of the large nails, Angus et al. found that there were several zones containing distinctly different microstructures indicative of high-carbon areas and low-carbon areas. Notably, the high-carbon areas extended down one side of the nail only or did not extend down the length of the shank to the point. An illustration of this effect is present in an iron nail from a site near the early Roman fort of Satala in eastern Turkey. (Figure 12) [24] The Romano-Turkish nail has material characteristics strikingly similar to the Inchtuthil nails with two contiguous zones extending down the full length of the shank: one low-carbon, one high-carbon. There is no indication of a weld plane in this nail or the Inchtuthil examples, which would indicate a deliberate joining of two different materials.

Explanations of how geographically disparate samples could have such similar specific material characteristics include coincidences of manufacture or centralised production of Roman iron. Further exploration is needed to test the repeatability of these types of microstructures in modern experiments and examine the shape, chemical composition and material characteristics of other early Roman nail samples.

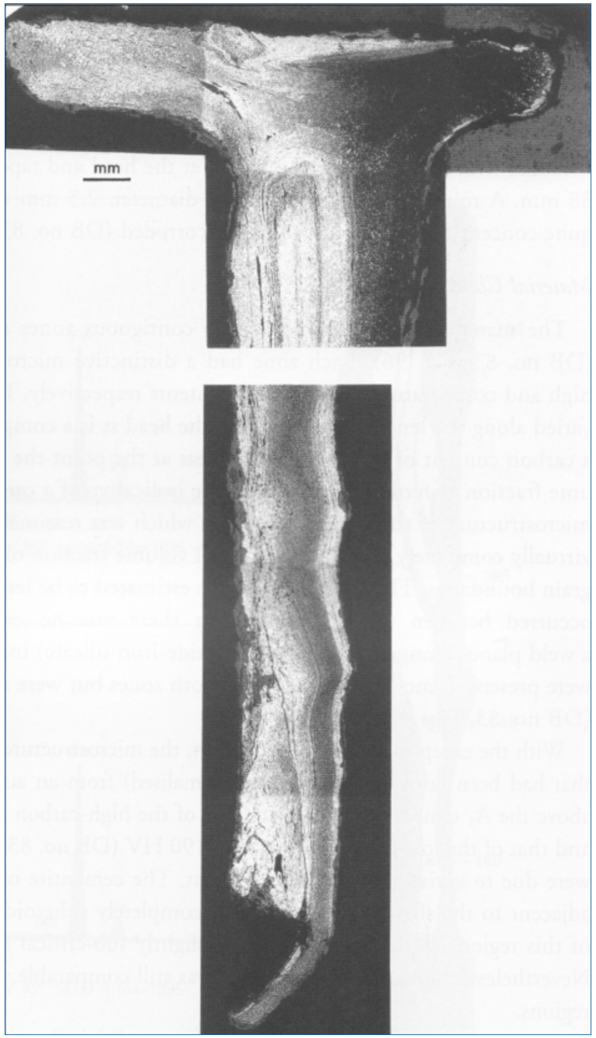


Figure 12: Photomicrographic mosaic of early Roman nail from eastern Turkey (head and point regions) showing contiguous zones of differing microstructures (light microscopy, longitudinal, 2% Nital etchant) [24]

Forging stage

Inchtuthil blacksmiths are likely to have heated the rod-shaped iron stock in the fire till red-orange, taken one rod out at a time, cut off the desired nail length and hammered all four sides tapering down the length to form a point. The smiths would then have reheated the nail at the head, inserted the nail point first into a nail heading tool and with blows of the hammer at a slight angle formed the so-called rosehead (the rough pyramidal shape) or with level blows of the hammer formed a disk-like flat head. It is not unreasonable to expect that a skilled smith would have produced high volumes of nails quickly, and may have also been able to distinguish between stock of iron that seemed to be particularly harder to work, and used that stock for larger nails. The scenarios described here have been reconstructed from the metallographic analyses conducted by Angus et al. and traditional blacksmithing practices. [25, 26]

The way in which one-sided zones of higher carbon iron appear in the Inchtuthil nails, often not extending all the way along the shank, is a peculiar feature for a nail. In theory, this composition is not optimal for ensuring the length of the tapered shank is rigid down its full length as it is driven into timber. For this outcome, one would expect all four edges of the shank and point to be equally hard. In fact, some of the Inchtuthil nails are examples of what a modern person might consider to be bad workmanship, with large fissures in the iron representing insufficient consolidation of the original stock, and many of the Inchtuthil nails, including all the items in the Abbott group, having eccentrically-positioned heads. There is further insight into the skill of the nail makers of the fortress. Kapusta and Underwood documented the fracture surface of an Inchtuthil nail (Angus et al. Group D type) broken under embrittling conditions. [20] They found a series of forging defects in the form of cracks and fissures in the metal and concluded that the defects could have resulted in failure by cleavage fracture if improperly driven at low temperature. The materials evidence indicates variability in the chemical composition of iron stock used by the Romans for nails and variability in fabrication quality.

Inchtuthil nails in the broader archaeological context

The archaeological and textual evidence suggests a great expansion of Roman-conquered territory and settlements in the later decades of the 1st century in Britain. [2, 27] An estimated 20 000 legionaries [28] would have meant a high demand for production and maintenance of iron weaponry, armour and tools. During this time, the Roman army was campaigning in the west and north of Britain and consolidating its conquests by building forts in conquered territories. Fortresses like Inchtuthil, with its barracks, officers' houses, drill hall, hospital, administrative buildings and workshops, were large with extensive superstructures of timber-framed buildings and wattle and daub walls, and required stocks of iron for structural purposes. [2, 29] The fact that the nails were made in such large quantities, theoretically exceeding the requirements for one fortress alone, suggests that they may have been kept in reserve at Inchtuthil ready for deployment to new forts as territory was secured and the northern frontier was advanced. [30] Based on attributable slag dumps (the waste products of iron ore smelting), there is conjecture that an average of 360 tonnes per annum of iron were produced between AD 43-100 for the province, covering the major settlement and production areas of the Weald, Forest of Dean and Jurassic Ridge. [27, 31] On this basis, seven tonnes of buried iron would represent about two per cent of the average annual iron produced for the province. By any account, this is a remarkable quantity of iron to have buried.

We can explore the economic and social value of the Inchtuthil nails a little more. Nails are simple, basic shapes in blacksmithing terms and are considered not difficult to make quickly and in large quantities. [26] Some of the materials evidence from Inchtuthil supports the notion that there was haste involved in fabrication, namely examples of asymmetrical, eccentrically-headed and poorly-forged nails. We should be mindful that the nails were utilitarian objects used to hold fast fortification walls, gates and other structures in military fortresses. The old adage that 'for want of a nail…the kingdom was lost' notwithstanding, the risk of catastrophic loss from improperly consolidated nails with eccentric heads is low. In other words, the nails were most likely fit for purpose and were made cost-effectively. From personal observations of modern blacksmiths who produce hand-made nails, the author estimates that on average an experienced smith can produce one small to medium sized nail in about 45 seconds if the stock is already red hot. Using this as a point of reference, it would take about 11 000 hours to produce more than 875 000 nails by hand. It is unclear if all the nails were produced at the site or if some were transported to Inchtuthil from the south. In any case, the quantity represents a significant investment of men and resources, including taking into account the need to mine, prepare ore and fuel, build furnaces and smelt the iron for stock. From this, we have an indication of the effort needed to make the Inchtuthil nails, and the economic value of the objects buried in the ground.

The legion's decision-making and problem solving can also be considered. A deliberate act such as burying seven tonnes of iron represents a myriad of possibilities concerning the conscious decision behind it. There are a number of examples of the Roman army hiding material and equipment that was scrap, damaged, or needing repair [30] but the Inchtuthil nails are notable because of the quantity of material buried and the fact that the nails were unused. There may have been an intention to return in the future to recover the stockpile, or the burial may have been made under duress, a hurried action where the logistical options of transporting seven tonnes of material were limited. The burial of perfectly good, unused iron suggests the material was commonly available and that there was confidence in the skill and adaptability of the Roman army to exploit other supplies, installations and systems quickly and effectively. Ascher suggests that researchers of material culture should be on the lookout for objects like the common nail as potential 'superartifacts' because they yield a special insight into the intellectual world of the people of a particular historical time in a way unmatched by any other object of the same period. [32] In the case of the iron nails from Inchtuthil, we have gained insight into production, technology and organisation of the imperial army. But we have also set the artefacts in a more personal context by discussing the production, fabrication and deposition of the nails in terms of less tangible concepts like confidence, experience, problem solving and expediency.

Finally, a word about archaeological finds, interpretation and conservation: a major liability of being able to interpret the past is the chance of survival of any artefact. If not for a fortuitous decision by the Roman legion to bury a stockpile of iron, coupled with favourable deposition conditions and the perspicacity of an archaeologist who noticed a change in soil colour, we would not be in the same position today to discuss corrosion processes, the skill of Roman nail-makers and the organisation of the imperial army. Certainly Mr Abbott's family would not have had the chance to be the custodians of five Roman nails and to present them to the Australian National University Classics Museum, generating new interest in a famous archaeological discovery from the 1950s. Conservators and materials researchers take their responsibility for preserving and interpreting material culture seriously, respectful of the human intelligence behind the object, and mindful of the opportunity to interpret and understand more about the collective past. Our research of the Abbott group nails, particularly assessing their condition and analysing their state of corrosion, was a critical step in conserving the objects for future generations to appreciate and study.

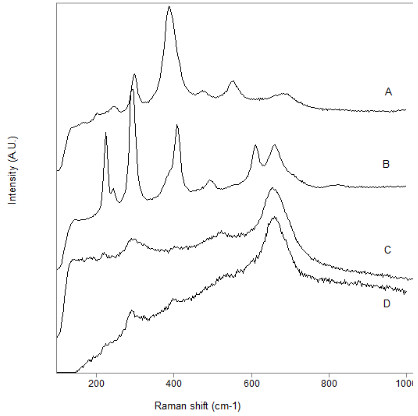
Appendices: Tables & Graphs

Appendix 1: Tabular results of Raman peaks relating to surface analysis of A1, A2 and A3 Raman spectrometer 633 nm radiation HeNe laser, University of Canberra

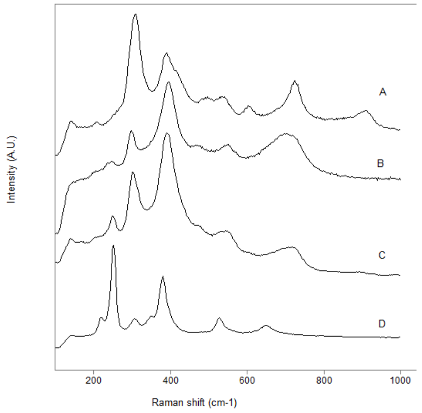
No.	Sample description	Likely compound identified	Raman shift/cm^{-1}						
1	A1 mid shank brown oxide 1	magnetite (Fe_3O_4)	660						
2	A1 mid shank brown oxide 2	magnetite	219	297	522	656			
3	A1 mid shank brown oxide 3	goethite (α-FeOOH)	245	298	390	475	553		
4	A1 mid shank brown oxide 4	unknown	215	277	392	590			
5	A1 mid shank brown oxide 5	feroxyhite (δ-FeOOH) and magnetite	290	400	657				
6	A1 mid shank brown oxide 6	haematite (Fe_2O_3)	226	245	293	410	610	660	
7	A1 mid shank yellow oxide 1	goethite	249	299	384				
8	A1 mid shank yellow oxide 2	goethite	252	299	386				
9	A1 mid shank yellow red oxide 1	lepidocrocite (γ-FeOOH)	220	251	309	379	528	655^{br}	
10	A1 point white adherent	High fluorescence and low Raman signal							
11	A2 under head brown oxide 1	predominately goethite	249	301	390	546^{br}	712^{br}		
12	A2 under head brown oxide 2	predominately goethite	248	300	391	550^{br}	707^{br}		
13	A2 under head brown oxide 3	predominately goethite	251	299	389	554	684^{br}		
14	A2 under head brown oxide 4	lepidocrocite	219	250	306	348^{sh}	378	528	650^{br}
15	A2 under head yellow red oxide 1	predominately haematite	218	287	398	605^{sh}	660		
16	A2 under head yellow red oxide 2	predominately goethite	298	394	547^{br}	705^{br}			
17	A2 under head yellow red oxide 3	lepidocrocite	219	251	307	348^{sh}	379	528	649^{br}
18	A2 point brown oxide 1	predominately akageneite (β-FeOOH)	207	308	390	538	605	724	911^{br}
19	A2 point brown oxide 2	feroxyhite-uncertain	298	394	685^{br}				
20	A2 point brown oxide 3	goethite	247	297	393	547^{br}	705^{br}		
21	A2 point yellow red oxide 1	haematite	221	288	402	490	605		
22	A2 point yellow red oxide 2	akageneite	310	390	542	722			
23	A3 shank fissure glassy brown 1	akageneite	310	390	410^{sh}	489	537	605	725
24	A3 shank fissure glassy brown 2	akageneite	310	389	416	489	539	605	725
25	A3 shank fissure glassy brown 3	akageneite	310	388	416	489	537	604	723
26	A3 shank fissure yellow oxide 1	akageneite	305	387	415^{sh}	487	538	603	722
27	A3 shank fissure red oxide 1	haematite	226	244 br	293	409	493	540	609
28	A3 shank fissure red oxide 2	goethite	204	245	299	386	417^{sh}	480	549
29	A3 shank fissure red oxide 3	goethite	204	245	299	387	415^{sh}	479	549
30	A3 shank fissure red oxide 4	akageneite	309	388	413^{sh}	489	537	604	723
31	A3 shank fissure red oxide 5	akageneite	308	389	415^{sh}	489	538	603	725
32	A3 under head yellow 1	goethite	205	247	300	387	477	552	707^{br}
33	A3 under head brown 1	goethite	219	251	301	386	477	543^{br}	688^{br}
34	A3 under head dark brown 1	goethite	301	389	480^{br}	560^{br}			
35	A3 under head dark brown 2	6-line ferrihydrite ($Fe_5O_3(OH)_9$)	252	380	505	711			
36	A3 under head dark brown 3	6-line ferrihydrite and goethite	252	301	385	517^{br}	715		
37	A3 under head yellow red 1	goethite	250	300	390	476	557	697^{br}	

Double underline = strongest peak, single underline = next strongest peak, ^{sh} shoulder, ^{br} broad peak
Cornell and Schwertmann reference series [13]

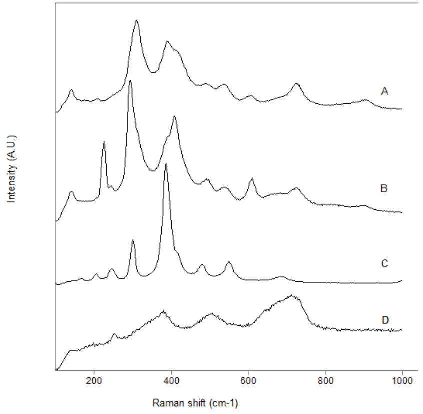
Appendix 2: Selected Raman spectra of surface analysis of nails A1, A2 and A3
Raman microspectrometer 633 nm radiation HeNe laser, University of Canberra



Graph 1 – Selected samples from nail A1
A – Sample 3
B – Sample 6
C – Sample 2
D – Sample 5



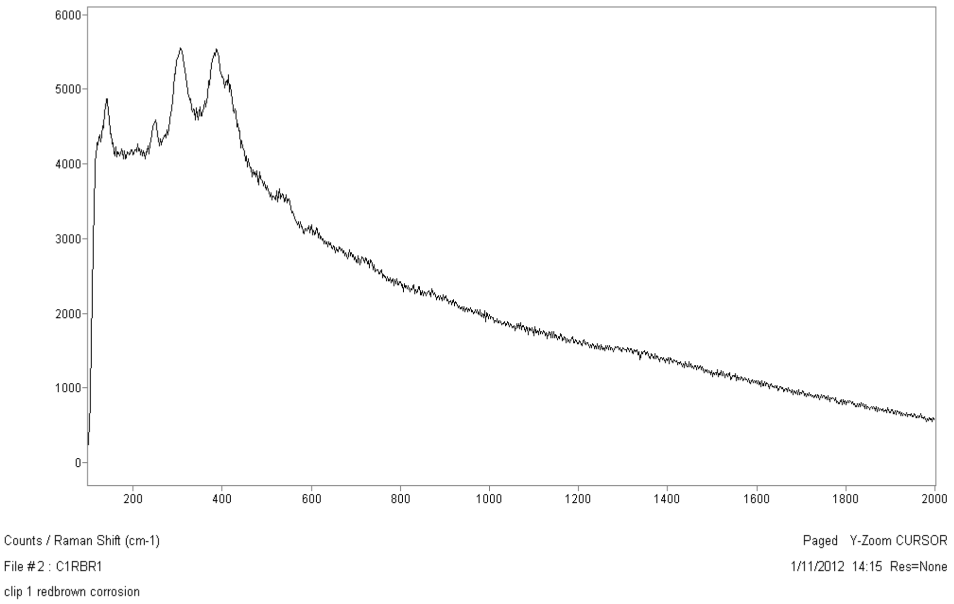
Graph 2 – Selected samples from nail A2
A – Sample 18
B – Sample 20
C – Sample 11
D – Sample 14



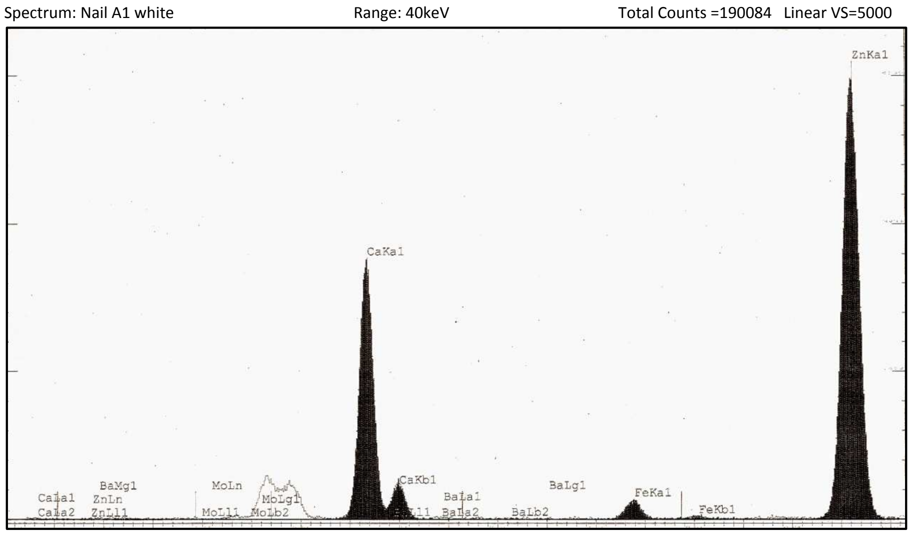
Graph 3 – Selected samples from nail A3
A – Sample 23
B – Sample 27
C – Sample 28
D – Sample 35

Appendix 3: Results of spot-tests on copper-alloy clip and nail A1 adherent

Graph 1: Raman spectra of surface analysis of copper-alloy clip in contact with nail A2. Peaks at 140, 250, 305, 385, 411, 538 cm^{-1}.
Raman microspectrometer 785 nm radiation laser, University of Canberra



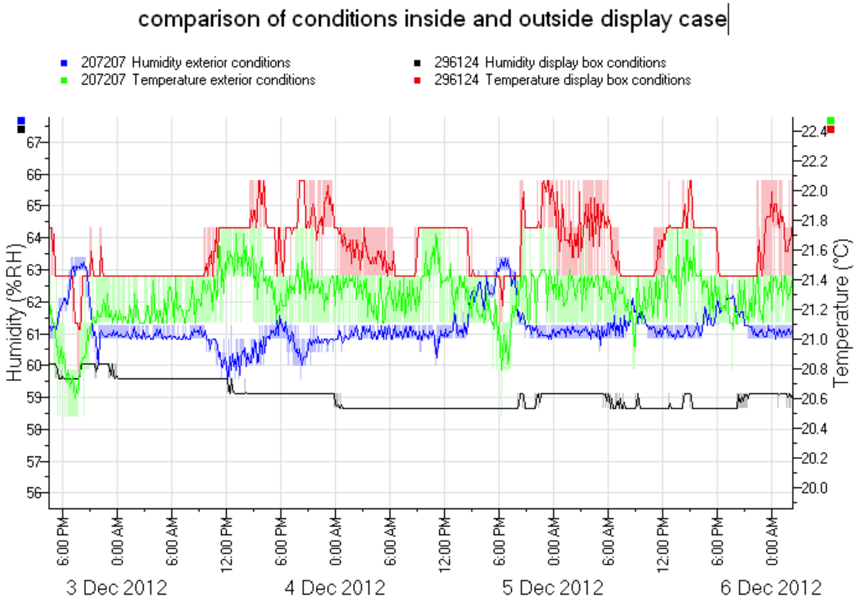
Graph 2: Results of XRF analysis of A1 white adherent.
Kevex Omicron XRF spectrophotometer: 40keV, 3mA, University of Canberra



Note: the unassigned peaks on the left hand side of the graph are from the XRF instrument tube.

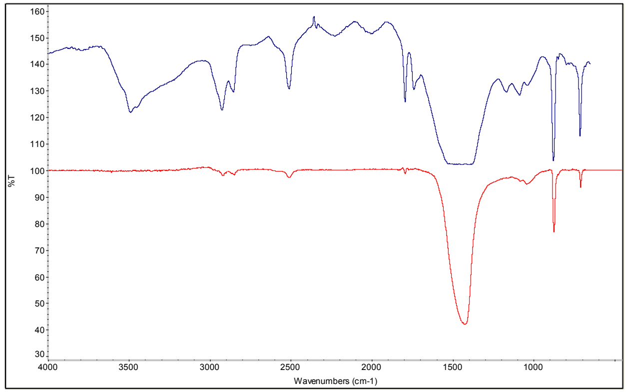
Appendix 4: Relative humidity and temperature inside and outside the wooden box

Graph 1: Relative humidity (RH) and temperature (°C) over four days



Appendix 5: Results of FTIR transmission spectra on A1 and steel staple samples

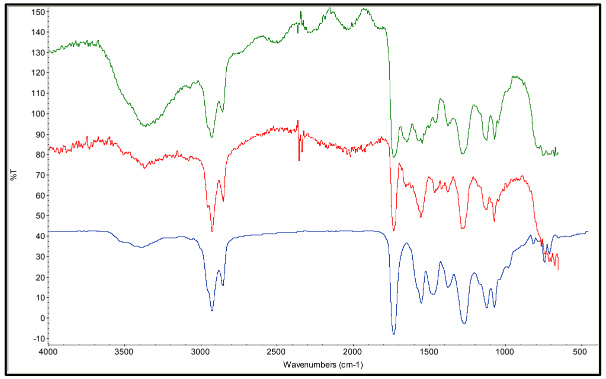
ThermoNicolet Nexus FTIR Continuum microscope in transmission mode, 64 scans, 4cm^{-1} resolution, University of Canberra



Graph 1

—A1 point, white adherent

—Calcium carbonate reference

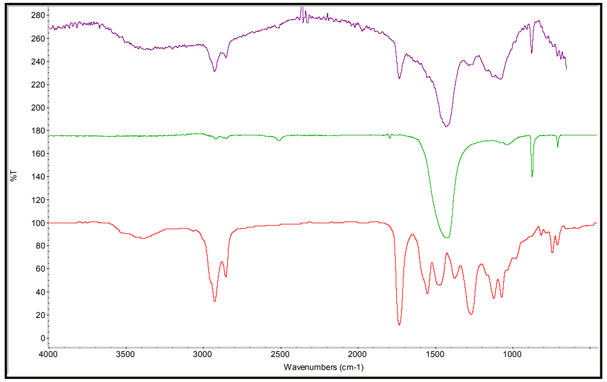


Graph 2

—Steel staple, cream coating

—Steel staple, green deposit

—Alkyd resin reference



Graph 3

—Steel staple, brown-coloured coating

—Calcium carbonate reference

—Alkyd resin reference

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