P.5

Understanding the economic influence of the dyeing industry in Pompeii through the application of experimental archaeology and thermodynamics

Heather Hopkins[1], Lorna Watling[2], Rob Janaway[1], Damian Robinson[1], Bill Seale [2]

[1] Department of Archaeological Sciences, University of Bradford, Bradford, BD7 1DP
[2] Department of Mechanical Engineering, University of Bradford, Bradford, BD7 1DP

Abstract

The influence of the dyeing industry in Pompeii on the local economy has been under discussion since the publication by Moeller in 1976. Since no absolute answer has emerged, the question was re-examined using two additional methods, experimental archaeology and the principles of thermodynamics.

A full-scale replica of a dyeing apparatus from Pompeii was constructed and used to simulate repeated dye runs, and so determine operating parameters such as the times involved to heat and cool a vat and the consumables needed. This first replica also allowed a better understanding of how the apparatus was actually used. Thermodynamic principles, which were applied to understand the successes and failures within the experimental work, suggested that the vat operated in a predictable way and enabled the operational mechanics of the vat to be established.

It is now possible to use both the experimental results and the thermodynamic modelling to determine not just the consumables used, but also the working environment needed for the vat to operate, allowing an understanding of the limitations to dyeing and to workers. Issues of practicality such as storage of consumables and disposal of exhaust gases may now be thoroughly examined.

Eventually it will be possible to determine the operating parameters of each of the dye vats, the quantities of consumables involved and the amount that could be produced. This should help answer the question as to the significance of the dye industry in Pompeii to the local economy.

Key Words: Heat transfer, Reconstruction, Dye vat, Pompeii, Economy

Introduction

The role of the textile industry in Pompeii, in particular its contribution to the urban economy, has been the subject of debate since Moeller's *The Wool Trade in Ancient Pompeii*, (Moeller, 1976). Moeller identified a number of structures throughout the city as pertaining to the textile producing industry, and concluded that 'there must have been considerable surplus for export'. Jongman (Jongman, 1988) heavily criticised Moeller's work claiming that the industry was in fact far smaller than had been previously thought, only capable of supplying Pompeii. Unfortunately, subsequent studies have been based on the same evidence as Moeller and Jongman's, namely study of the remains *in situ* and review of the published literature. At present this alone is insufficient to allow a full understanding of the textile industry and its contribution to the economy of Pompeii and its Hinterland.

This study aims to approach the question of the economic significance of the textile industry in a new and interdisciplinary way. Experimental reconstruction and the application of heat transfer principles from the field of engineering will test the assumptions of previous authors and provide new evidence of how the dye plants operated. Moeller's identification of dyeing apparatus and workshops shall be reevaluated and their operation reassessed. A recalculation of the capacity of each dye works shall be viewed in context with the population of Pompeii, to finally determine the scale of the economy. This finding shall withstand greater scrutiny, as it shall be based not purely on observation of the remains and published literature, but also on the operating parameters of a dye vat, determined through experimental reconstruction and application of heat transfer and other principles.

To understand the operating parameters of a dye vat and the dyeing process, a copy of a small dye vat apparatus was constructed and used to replicate dyeing with madder. The replica was constructed from modern materials, their properties compared with Roman materials using the heat transfer principles. Heat transfer principles were used to model the vat. The replica vat and engineering theory had been developed independently, but were then combined to produce the fuel consumption model. Following this the vat was amended to include a flue. The difference this made to the operating parameters was noted and the model was calibrated using the flued dye vat. Throughout this paper the first reconstructed vat (without the supplementary flue) will be referred to as the unflued vat and the modified vat (that includes the supplementary flue) will be referred to as the flued vat.

Textiles do not tend to survive well in the archaeological record, (Watkinson and Neal, 1998:65; Harris, 1999:8), hence finds of Roman textiles are a rarity. The Masada textiles have been preserved to an extraordinary degree, the original dyes still being discernable, and represent the largest collection of Roman textiles discovered, (Sheffer and Granger-Taylor, 1994). Wool appears to have been the most commonly used and most commonly dyed material, (Sheffer and Granger-Taylor, 1994; Frayn, 1984:142-161). Madder is the most common dye found in the plant record. (Walton-Rogers, 1997). Madder was certainly in widespread use as a dye, (Ponting, 1980), and has been discovered in textiles throughout the Roman world. (Koren, 1994; Taylor, 1987). Of the dyes that were found in the Masada textiles, only madder could be identified from the dye back to the plant, (Koren, 1994), as the chemistry of madder is such that it may be unambiguously identified. Therefore it was decided that the vat would be used to replicate madder dyeing.

Dye vat design

A dye vat is an apparatus used for dyeing wool, textile or yarn. It consists of a metal kettle, containing the material to be dyed, dye and water. This is supported in a brazier so that the kettle is held above a fire. The fire provides the heat for the dyeing reactions to take place and must be carefully monitored. Figure 1 shows the parts of a dye vat.

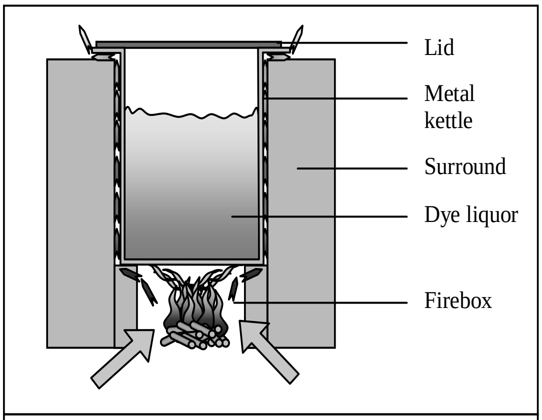

Figure 1. Diagram showing the parts of a dyeing apparatus. The arrows indicate the natural "flue" that exists in an unflued vat.

Figure 2. Flued dye vat from VII xiv 17, kettle *in situ*, replicated in reconstruction.

Prior to dyeing the wool is cleaned ("scoured") and "pre-mordanted", (Frayn, 1984; Grierson, 1986). Mordanting is the process by which the wool is treated with a chemical (normally a metal salt) to allow the dye to stick. To dye the wool it is placed in the metal kettle of the dye vat once the dye within the vat has dissolved in the water and reached the correct temperature. The wool and "dye liquor" are then simmered and the kettle left to cool naturally. This allows further dye to stick and a stronger, faster colour to result.

Control of the fire through the firebox is extremely important, as while the dye liquor must simmer, it must not be allowed to boil. Boiling ruins the fleece and causes changes to the dye possibly resulting in a different colour, (Storey, 1978). The fire (and therefore temperature) is influenced through the fuel amount and the airflow.

Energy is released from the fuel during the process of combustion. The amount of energy per mass of fuel is quantified in the form of the calorific value of the fuel. The energy raises the temperature of the air above the fire, causing it to become less dense, the air rising upwards away from the fire. As the air leaves the fire it draws in new air containing more oxygen. This causes the fire to sustain itself. If the amount of air drawn in is insufficient the fire is extinguished, as there is insufficient oxygen to sustain combustion. (Rossotti, 1993). If a flue is present the change in density of the warm air (the density between the air at the base when compared to the air at the top of the flue) allows it to rise up the flue. (Fullick, 1994; Çengel and Boles, 1998). Therefore the draw is greater in a fire assisted by a flue. While the air travels up the flue it loses heat to the sides and so indirectly heats the vat. While the only thing driving the movement of the air is the heat generated by the fire, it should be noted that the combustion may only be sustained if the movement draws sufficient new air. A flue allows the increased movement of air as the exhaust air may be released in a greater volume thereby increasing draw. The arrows in figure one show the natural “flue” that exists in an unflued dye vat.

Methodology

A replica vat was constructed based on measurements and photographs from Pompeii (see table 1). The vat was a replica based on the design of vats within property VII ii 11, (see colour plate). The kettle was manufactured from stainless steel. The design was based on the kettles that remained in properties 1 viii 19 and VII xiv 17 (see figure two). The recipe that was used included just madder and alum (Story, 1978) and required the vat to contain 90 litres of water, which were then heated to 95^{o}C and held at that temperature for 1 hour. The vat was then allowed to cool naturally with the fleece and water still in place. While no madder or alum was actually used their presence was allowed for. The effect of lead and madder on fleece was examined through laboratory work.

The operating parameters that were tested included the time it took for the vat to heat and cool, and the amount of fuel that the vat required. The fuel used was pine, not because it was believed that pine had been used in antiquity, but because it provided a uniform fuel from which the calorific value could be calculated. Heating with charcoal was also attempted. Methods of emptying and cleaning the vat were also assessed. The flued vat was tested in the same way.

There is little evidence for or against the use of a lid. As yet a lid has not been discovered through excavation. The pictorial evidence is unclear. The subject depicted in the wall painting outside Verecundus's workshop in Pompeii (Wild, 1970) is still debated. The other notable picture is from a tombstone in Arlon, Belgium (Wild, 1970) and depicts the stirring of a dye vat, an activity that took place with the lid off, and so there is no lid depicted in this picture. This had led to the conclusion that a lid was not used in antiquity in conjunction with these dye vats. However calculations of heat lost and matter transfer (water evaporating) during the experiment demonstrated that a lid was required when heating the vat. A wooden lid of 2cm thickness would have halved the heat lost through the top of the vat. The water loss without the lid would have led to the ruin of the fleece.

The dyeing process in Pompeii would have been similar to processes carried out through history. The fleece would have first been pre-mordanted – it would have been heated in a vat containing the mordant, usually alum, (Grierson, 1986; Sheffer and Granger-Taylor, 1994) dissolved in water. Following this a vat containing the dyestuff dissolved in water (90 litres for a 2kg fleece) would have been heated, and the fleece added. The fleece would have been simmered for an hour and then be allowed to cool naturally. The heating allows the activation of the dye and cooling within the dye liquor allows the dye to stick to the fleece.

The dye kettles from Pompeii were originally manufactured from a lead-based alloy. Heat transfer calculations showing what was used in the replica was similar to the original, (Çengel and Boles, 1998). Lead was most suitable as a dye vat material as alternative metals, such as copper and bronze, are mordants and sadden (darken) or alter the dyestuff. Lead is also a mordant, but brightens the colour by increasing the uptake of dye by the cloth. The disadvantage of lead that its strength in relation to its weight means that it is fragile, especially after repeated heated and cooling (as creep may alter the shape). (Pers Comm. Wright, 2004). It is not possible to lift the vat or for it to support its own weight. This means that construction and repairs must take place *in situ*, as it would not be possible to lift a vat into a brazier.

Implementation of Engineering Theory

Part of the study into the economic impact of Pompeii's dyeing industry required an assessment of the quantity of fuel used. Results from the experimental work were not directly transferable due to the use of modern materials in the reconstruction. However this was not an insurmountable problem given that the experiments gave actual results for a measurable system. The results from the experiments could be used to understand and quantify the heat transfer processes taking place within the system during operation. By accounting for the energy required by various parts of the system it is possible to calculate the quantity of fuel necessary to run the system, (Çengel and Boles, 1998).

It was also realised that a study of this nature could enable a better understanding of the system through analysis of the variables applied to the system and how great an affect on the fuel used changing those variables would have. This would require a model to be created for finding the fuel consumed so that variables could be tested without altering any of the other operating parameters. An understanding of which variables have the most influence on the fuel consumed will be invaluable in future reconstructions involving heat transfer.

Below is a simplified version of the system that was examined.

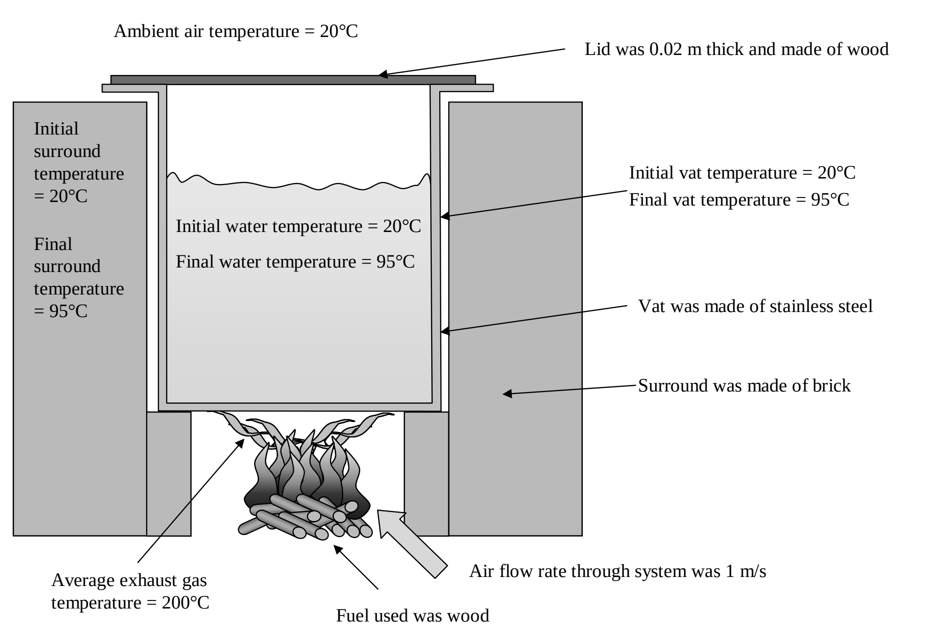

Figure 3. Diagram showing initial parameters used for calculations.

It was noted through experimental work and heat loss calculations that energy was lost through the following ways (parts are labelled on figure one):

1. Heat was lost through the top of the vat
2. Energy was required to heat the vat to steady state temperature
3. Energy was required to heat the surround to steady state temperature
4. Energy was required to heat the water to steady state temperature
5. Energy was lost through the walls of the vat
6. Energy was lost to the air flow through the system
7. Energy was lost to the ground

A set of calculations to account for the energy lost in the processes described above were established (Çengel and Boles, 1998; Diamant, 1986; Holman, 1981, 2002;

Edwards et al, 2002) and this could be used as the basis of a model for the fuel consumption of the dye vat.

The model created was calibrated using the data from the experiments done on the modified vat (flued version). This gave an error within the model of ± 0.5 kg. This quantity of fuel was arrived at using a calorific value of 15,800 kJ/kg (Cooper & Rose, 1977).

The variables examined for the affect they had on the fuel consumption were the surround material, vat material, initial water temperature, final water temperature and ambient air temperature. The effect of changing the quantity of water was also briefly examined. Prior to examining the materials it was important to establish which property of the materials that had been used in the calculations was causing the greatest change in the results for the fuel consumed. (Callister, 2000; Çengel and Boles, 1998) The three properties of the materials that were examined were specific heat capacity, thermal conductivity and density. The specific heat capacity is the energy required to raise 1kg of a substance by 1 degree (when using the units kJ kg^{-1} K^{-1}). The thermal conductivity is the rate of flow of energy through a material of thickness 1m and with a temperature difference of 1 degree between the two sides of the material (when using the units W m^{-1} K^{-1}). Density is the mass per unit volume (kg m^{-1}). (Callister, 2000; Çengel and Boles, 1998, Fullick, 1994). It was found that the specific heat capacity had the most significant affect and hence materials with relatively high, medium and low specific heat capacities were used for the material evaluation.

The results of the key factors assessment are shown below:

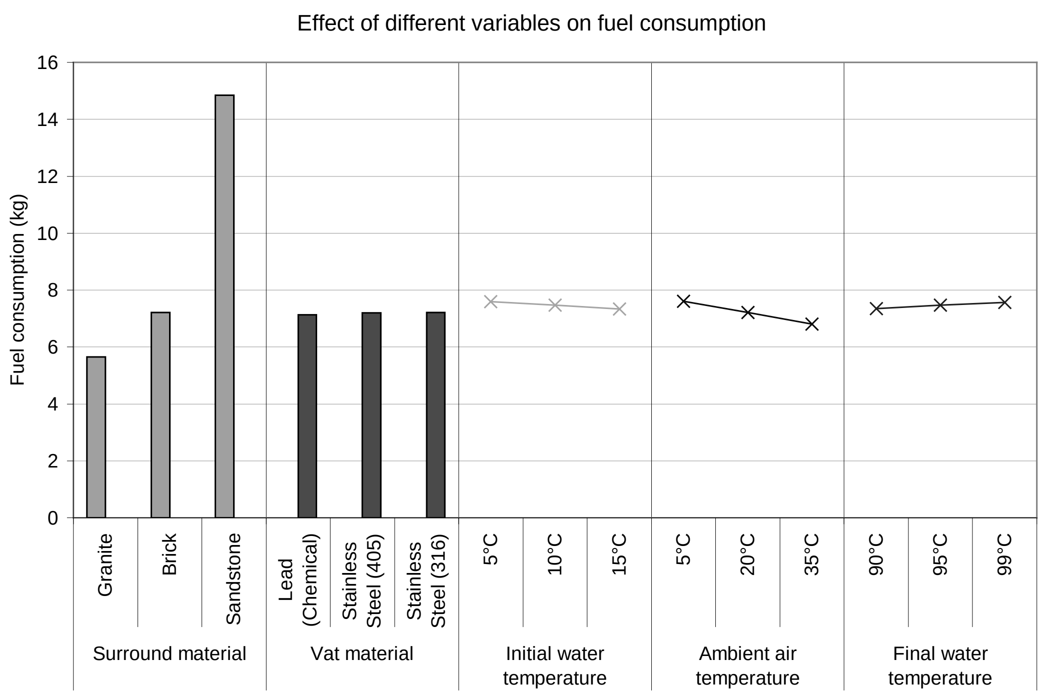

Figure 4. Effect of different variables on fuel consumption

In each of the cases only the variable being examined was changed. The actual values for the fuel consumption are relative. This is because only the variable being examined was changed. The important part of this graph is the scale of changes in the fuel consumption for likely changes in the variables. The affect of changing the surround material has the greatest effect on the fuel consumed. This means that it will make little difference to the results acquired if say the air temperature was 20°C different to the temperature in Pompeii or if the vat material was made of stainless steel instead of lead.

The next part of the study was to examine output of the other vats in Pompeii. The results for the flued vats did not follow the expected trend and it is believed that this is due to the assumption that all the flues had the same dimensions as the one of the replica. This was a necessary assumption because no other information on the flues attached to the vats in question was available. The results are shown in the graph below:

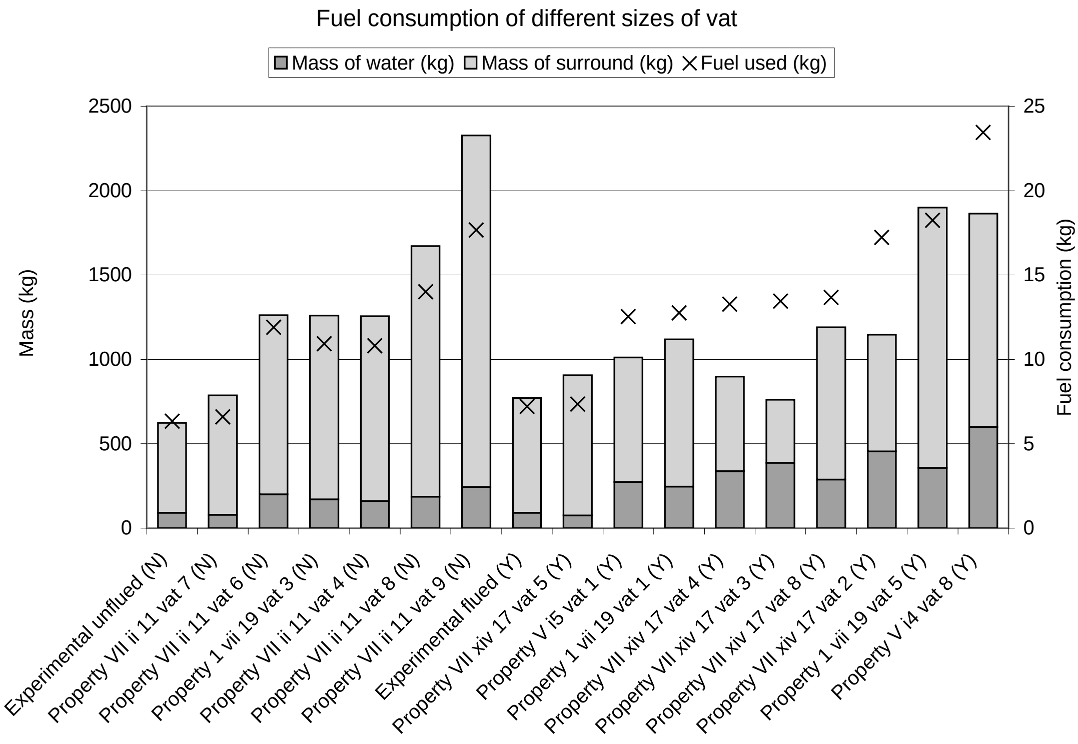

Figure 5. Effect on fuel consumption of different sizes of vat. (N) indicates that no external flue was present. (Y) indicates the presence of an external flue.

During the previous assessment it was assumed that the volume of water in the vat was constant. Whilst examining the results for other dye vats found in Pompeii it became apparent that the effect of water was of a similar order of magnitude to that of the surround material. This was investigated further and it was found that the water has a more significant impact on the fuel used than the surround material. Therefore if the dye vat was to be run with say 130 litres of water instead of 90 litres the fuel used would be significantly greater even if you removed 40 litres worth of bricks from the surround structure.

This work has provided the basis for further study into the understanding of the working of the system.

Results

It was noted that despite various attempts and methods charcoal would not light and sustain combustion in the unflued vat, and would light but then extinguish shortly after ignition in the flued vat. Wood was able to burn easily in either vat, with no external source of ventilation or through draft. On average the unflued vat would take two hours to heat, would be held at temperature for one hour and then would take in excess of four hours to cool. The unflued vat behaved similarly, but the flame control was greater and less flame and smoke came out of the front of the vat. Between six and seven kilograms of wood was required to heat either vat, a quantity that translates to a modern dustbin bag. This is equivalent to 120,000 kJ, if the calorific value of the wood is taken as 15,800 kj/kg. (Cooper and Rose, 1977).

The fleece broke up considerably in the vat and the madder tangled with the fleece. This would have resulted in the drains on the plumbed-in vats blocking and the fleece to become irregularly coloured or extra time and effort being taken to untangle the fleece.

The average time taken for heating the vat was two hours to heat, one hour to simmer and then at least four hours to cool. From this it was seen that the vats could not have been heated more than once a day. The water must cool naturally with the dye and fleece within it otherwise the dye will not combine with the fabric, (Storey, 1978). Therefore the vats may only have been heated once a day.

It has been assumed that each fleece needed 90 litres of water to allow successful dyeing (a lesser amount would not enable the fleece to move freely). The amounts of fleece that each dye vat could contain was calculated. As the vats were not constructed according to metric, it was difficult to determine the amount of fleece some of the vats could contain. Therefore each vat was given a minimum and maximum amount that it could have contained. This may be viewed in table 1. The maximum and the minimum calculations give a boundary to the maximum amount of dyed fleece that it was possible to produce in Pompeii each working day.

Minimum: 15 + 28 + 13 + 40 + 39 + 19 = 154 fleeces per day

Maximum: 17 + 32 + 16 + 41 + 42 + 19 = 167 fleeces per day

It would have been possible to dye between 154 and 167 fleeces a day in Pompeii.
There were 318 working days in Pompeii.

Minimum: 154 x 318 = 48, 972

Maximum: 167 x 318 = 53, 106

Between 48, 972 and 53,106 fleeces could be dyed in Pompeii per year.
It was assumed that the population of Pompeii was 12,000 people, (Storey, 1997). If these totals were to be divided evenly between the population of Pompeii, the average would give an estimation as to the size of the industry in terms of its capacity to provide the populace with all of their textile needs. If the number produced per person was extremely large, this would immediately suggest export. If the number produced was not excessively large, this would result in a need for extra research into the scale of the industry.

$\frac{48,972}{12,000} = 4.081$ This may be rounded down to 4 fleeces per person.

$\frac{53,106}{12,000} = 4.4255$ This may be rounded down to 4.4 fleeces per person.

Ryder states that the closest fleece to that of a Roman fleece (in terms of size, weight and make-up) is that of a Shetland sheep, (Ryder 1990). Therefore a fleece was taken as weighing approximately 2kg.

4.081 x 2kg = 8.162 kg 4.42 x 2kg = 8.84 kg

Therefore between 8.162 kg and 8.84 kg dyed fleece was produced annually per person in Pompeii. This may sound like a lot. However, in modern terms this is a "washing machine load" (albeit a large one). It could therefore be reasoned that the dyeing industry of Pompeii was extremely small, possibly specialist, and not of a scale large enough to export, (as Moeller, 1976, had suggested).

This issue is confused by the use of dyed textile as a decoration and not the main piece of some garments. This custom would mean that the amount produced could be an underestimate. However, production of some items, such as curtains, would require such an amount that a larger quantity would be required than it appears.

It may also be supposed, following the practical experiment, that to operate the dyeing apparatus alone would have only taken a relatively small amount of labour. It took two people minimal effort to run the single apparatus used in the reconstruction once it was alight and functioning. Although it may be seen that the smallest number of dye vats was three in a property, and that the properties usually had more than just dyeing apparatus, it may be supposed that the actual dyeing itself was not a labour-intensive task.

Following review of the skeletal data (Capasso, 2001), it was noted that two of the authors were exactly the height of the average male and female Roman. Following closer examination of the original vats it was determined that both authors were able to use each one, and would even have been able to clean the base of each one.

It was noted that vats in enclosed properties had flues, despite their size, where as vats in more open properties did not, unless the vat was particularly large. Following the practical work and the examination of the property, it is believed that this is linked to the ventilation of each vat and the relative airflow. The finding is further supported as in an entirely open environment the flow did not appear to make a significant difference to ventilation, although it did alter the controllability of the flame.

Conclusion

Following the experimental work, engineering work and further literature review the following conclusions could be made about how the vat operated.

Conclusions that may be drawn regarding the operation of the vat:

- The fuel was wood or a fuel that had similar calorific value per weight. It was not charcoal.

- The quantity of fuel used may have been a limiting factor.

- The presence of a flue in the original vat indicated a difficulty in causing adequate airflow of that vat.

- The dye works may have been operated by a small number of people, between one and three. However this does not exclude a larger workforce.

- All of the vats were usable by an average Roman. Vats that at present would not be usable show signs of having been altered. The original heights of all of the vats are discernable and these were usable. This would mean that height would not have restricted the workforce.

- A lid was used during dyeing. This was probably constructed from wood.

- The vats were heated and cooled once a day. It is most likely that they cooled overnight and were emptied in the morning, as they would have taken at least fours hours to cool naturally.

- The quantity of water used had the greatest effect on the amount of fuel required to heat the vat. If the water quantity remained the same, the material used for construction of the brazier had the greatest effect on the quantity of fuel required.

Conclusions that may be drawn regarding the influence of the dyeing industry on the economy of Pompeii:

The industry was not large enough to export. However, it was large enough to supply Pompeii and possibly the hinterland. The use of dyed material as a decoration and not as the main body of some garments may have led to an underestimation of the figure produced, but the need to scour the textile and the use of scouring plants leads to the conclusion that this is not a vast underestimate. Moeller's findings are still an overestimation.

Table 1, showing the possible minimum and maximum outputs of each dye works per day. The amount of fleeces were determined assuming that each fleece require 90 litres of water.

Regio	Insula	No.	Type	Flue	Internal Diameter (cm)	Internal depth (cm)	Vol. (l)	New maximum	New minimum
I	Vii	19	1 vat	Y	98	51+	384.69	4	3
			2 vat	N	Circ 2.64m	54+	299.26	3	3
			3 vat	Y	74	63	270.95	3	3
			5 vat	Y	97	75	554.23	6	5
			7 vat	Y	40-50	50	80	1	1
							Total:	17	15
V	I	4	4 vat	Y	97	80?	229+(591?)	6	5
			5 vat	?	61	52+	151.97	2	1
			6 vat	Y	120	80	904.77	10	10
			7 vat	?	74	78+	335.47	4	3
			8 vat	?	120	81	916.09	10	10
							Total:	32	28
V	I	5	1 vat	Y	95	60	425.29	5	4
			2 vat	N	50	under 91	178.68	2	1
			3 vat	N	99	68	523.44	6	5
			4 vat	Y	85	69+	319.54	3	3
							Total:	16	13
VII	Ii	11	1 vat	N	106	69?	608.91	7	7
			2 vat	N	106	74?	653.03	7	7
			3 vat	N	96	60?	434.29	5	4
			4 vat	N	76	56?	254.04	3	2
			5 vat	N	50?	43?	84.43	1	1
			6 vat	N	86	54?	313.68	3	3
			7 vat	N	55	55	130.67	1	1
			8 vat	N	99	38+	292.51	7	7
			9 vat	N	94	55+	381.69	7	7
							Total:	41	40
VII	Xiv	17	1 vat	Y	68	50	181.58	2	2
			5 vat	Y	117	65+	698.84	8	7
			6 vat	Y	100	76	596.90	7	6
			7 vat	Y	99	68	523.44	6	5
			8 vat	Y	60	43+	121.58	1	1
			9 vat	Y	109	48?	447.91	5	5
			10 vat	Y	68	51+	185.22	2	2
			11 vat	Y	95	63	446.56	5	5
			12 vat	Y	51	43	87.84	1	1
			13 vat	Y	94	60	416.39	5	5
							Total:	42	39
Ix	Iii	2	1 vat	N	73	133	556.66	5 (new 6)	5 (new 6)
			2 vat	N	83	130	703.37	6 (new 7)	6 (new 7)
			3 vat	N	90	135	858.83	8 (new 9)	8 (new 9)
							Total:	19	19

Bibliography

Capasso, L. 2001. *Palaeobiologia delle vittime dell’eruzione vesuviana del 79 d.c.* I Fuggiaschi di ercolano. <<L’Erma>> di Bretschneider

Callister, W.D. 2000 *Materials Science and Engineering: An Introduction*, John Wiley & Sons, Inc. New York.

Çengel, Y.A., & Boles, M.A. 1998 *Thermodynamics: An Engineering Approach*, McGraw Hill

Cooper, J.R. & Rose, J.W. 1977, *Technical Data on Fuel*, British National Committee World Energy Conference, pp 304-30

Diamant, R.M.E., 1986, *Thermal and Acoustic Insulation*, Butterworths,

Edwards, D.K., Denny, V.E., Mills, A.F., 1973 *Transfer Processes. An Introduction to Diffusion, Convection and Radiation*, Holt, Rinehart and Winston Inc. p139

Frayn, J. 1984. *Sheep-Rearing and the Wool Trade*. Francis Cairns. Liverpool.

Fullick, P. 1994. *Physics*, Heinemann Education Publishers, Oxford

Grierson, S. 1986. *The Colour Cauldron* Mill Brooks, Perth, Scotland.

Harris, J. 1999. *5000 years of Textiles*. British Museum Press.

Holman, J.P. 1981, *Heat Transfer*, McGrawHill

Holman, J.P. 2002, *Heat Transfer*, McGraw Hill

Jongman, W. 1988. *The Economy and Society of Pompeii*. J.C.Gieblen. Amsterdam.

Koren, Z. 1994. Analysis of the Masada Textile Dyes. In, A. Sheffer and H. Granger-Taylor. *Masada IV The Yigael Yadin Excavations 1963-1965 Final Reports. Israel Exploration Society* The Hebrew University of Jerusalem. pp257-264.

Moeller, W. 1976. *The wool trade of ancient Pompeii*. E.J.Bril:Leiden.

Ponting, K. 1980. *A Dictionary of dyes and dyeing*. Mills and Boon Ltd, London.

Rossotti, 1993. *Fire* Oxford University Press

Ryder, M. 1990. The Natural Pigmentation of Animal Fibres. *Textile History*, 21 (2), 135-48, 1990.

Sheffer and Granger-Taylor, H. 1994. *Masada IV The Yigael Yadin Excavations 1963-1965 Final Reports*. Israel Exploration Society The Hebrew University of Jerusalem.

Storey, G. 1997. The Population of Ancient Rome. *Antiquity*. 71:966-978.

Storey, J. 1978. *Dyes and Fabrics*. Thames and Hudson, London.

Taylor, G. 1987. Reds and Purples from the Classical World to Pre-Conquest Britain. *Textiles in Northern Archaeology*. NESAT III textiles symposium in York.

Walton- Rogers, P. 1997. *Textile Production at 16-22 Coppergate*. British Council for Archaeology.

Watkinson, D and Neal, V. 1998. *First Aid for Finds*. Lavenham Press.

Wild, J.P. 1970. *Textile Manufacture in the Northern Roman Provinces,* Cambridge University Press.

Wright, C.S. Pers Comms. 2004. Lecturer in materials, School of Engineering, University of Bradford.

Total Words: 4,987

Figure Captions:

Figure 1. Diagram showing the parts of a dyeing apparatus. The arrows indicate the natural "flue" that exists in an unflued vat.

Figure 2. Flued dye vat from VII xiv 17, kettle *in situ*, replicated in reconstruction.

Figure 3. Diagram showing initial parameters used for calculations.

Figure 4. Effect of different variables on fuel consumption

Figure 5. Effect on fuel consumption of different sizes of vat. (N) indicates that no external flue was present. (Y) indicates the presence of an external flue.

Table 1, showing the possible minimum and maximum outputs of each dye works per day. The amount of fleeces were determined assuming that each fleece require 90 litres of water.

Principle author: Heather Hopkins H.J.Hopkins@Bradford.ac.uk

Department of Archaeological Sciences,
University of Bradford,
Bradford,
BD7 1DP

Colour Plate

Unflued dye vat from VII ii 11, replicated in reconstruction