Reconstructing the dyeing industry of Pompeii through experimental archaeology: the challenges and rewards of a new approach

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To determine the scale of manufacture of the city of Pompeii would allow an understanding of its economic significance and its place in the Roman world. Pompeii, at the foot of the Mount Vesuvius, was destroyed by a volcanic eruption on August 24th 79AD. The destruction was swift and absolute: the pumice encased the buildings to the first storey, then the pyroclastic event removed and obliterated anything above this layer. What remained was encased in solid rock. Pompeii was a city frozen in time. Although a large number of the population had fled, taking artefacts with them, the industrial apparatus remained *in situ*, in their workshops within the city that they served. Pompeii therefore offers a unique opportunity to reconstruct the industries of a city, to determine the scale of manufacture and the place of the city in providing for itself, in exporting and in its place in the wider economic framework of the Empire.

When studying the destruction of Pompeii it is necessary to place it in context. The volcanic eruption was not the only event to devastate Pompeii as seventeen years earlier an earthquake had levelled parts of the city and caused the aqueduct to cease functioning. The magnitude of the event and the aftermath caused great change within the city. Laws were passed allowing the city to take uninherited property. As the residential areas were the first to be reconnected to the water supply it was in the interest of businesses to move there. This led to the establishment of dyeing workshops in former residences and other properties that ordinarily would not have been industrial. The city returned to a functioning way of life, then seventeen years later was destroyed, and encapsulated, through the volcanic eruption. Following this the city remained undiscovered until c1750AD, when it was first noted as a source of arts, treasures and materials to be plundered. It was only during the 19th and 20th centuries that archaeological exploration began in earnest.

The dyeing industry is of interest in reconstructing the scale of manufacture of Pompeii as a whole because it is the only industry whose apparatus may be unambiguously identified. A *fullonicae* (fullery) had multiple uses: it did not just full cloth but was also what modern parlance would term a laundrette. Also, the dyeing apparatus have survived relatively intact and *in situ*. They are each in the context of the workshop in which they would have operated, in context of each other and in context of the city that they supplied. Therefore when calculating their production capacity, any more than the city would have required could have been exported, any less and the city would have relied on imports.

Prior to the current study the understanding of the scale of manufacture of Pompeii's textile industry relied on theoretical assumptions applied to superficial measurements of surviving apparatus. Moeller undertook a survey of the apparatus and concluded that the industry had been large enough to export (Moeller, 1976). Jongman, using Moeller's data, concluded that the industry had been far smaller and that Pompeii relied on imports (Jongman, 1976). Subsequent studies agreed with Jongman's conclusion that the industry was smaller than Moeller originally thought, but each relied on Moeller's data and did not collect their own (e.g Laurence, 1994; Mann 1994). The studies were purely theoretical and did not attempt to recreate the process involved or a physical understanding of the apparatus. The realisation that forms the basis of this study, that to determine the output of an industry it was necessary to understand the apparatus involved and that to do this it was necessary to construct and use a replica, was entirely new. While there have been craft reproductions of dyed textile and analysis of the archaeological examples, there has been very little study of the method of production and until this study there had been no full scale or practical replication of Roman dyeing apparatus. The closest reconstructed apparatus was the cooking vessel of the 16^{th} century Mary Rose, the flag ship of Henry VIII. This had been a copper kettle with a lead flange placed in a brick embrazier, reconstructed for public instruction and entertainment.

Constructing and using a replica of a dyeing apparatus allowed an understanding of how such an apparatus worked, both how a dyer operated it and the physical principles behind how the apparatus was heated and dyed. To use an apparatus allows the cycle time, the time taken for heating, dyeing and cooling, to be determined. The fuel type and quantity required can be calculated. It was possible to see how the apparatus was physically operated and to undertake an ergonomic assessment of the design. During the construction it was possible to see and address any problems that arose. But most importantly, as prior to this study a replica had not been constructed or operated, it had not yet been proven that the apparatus in Pompeii were of a viable design. The construction of a replica not only allowed an understanding of the operation of the apparatus but also an assessment of whether additional elements were missing or had been changed since the apparatus were used in antiquity.

Planning the replica raised questions. Firstly, as the dyeing itself had to be undertaken without a break it would be disastrous in an experimental dyeing to run out of fuel. Therefore, it was necessary to determine how much fuel the apparatus requires. It was realised that in archaeology this was an unusual and possibly unanswerable question. However, in engineering this was a simple calculation relating to efficiency of the apparatus. The project for the first time began to depart from archaeology and theoretical classics and enter the realm of engineering.

When calculating the energy required to heat an apparatus, the materials that the apparatus are made from are an influential factor. The original materials used in Pompeii, a lead kettle and lime mortar, were banned through health and safety restrictions. It was necessary to use substitutes, but there were questions over what would be suitable. As Reynolds stated, to use different materials in the construction of a replica renders it an experience, not an experiment (Reynolds, 1999). The study wished to determine the fuel used in heating the apparatus and the time taken. Therefore the materials used had to be chosen to react in the same way as the originals, that is, they should warm and the heat should pass through them the same way as the original materials used. Stainless steel was chosen to replace lead as the thermal conductivity of lead is 35 W/mK while stainless steel is 27 W/mK (Callister, 2000). In context, aluminium is 235 W/mK, so it may be seen that lead and stainless steel are seen as equivalents. The brick used had the same thermal conductivity as the brick, rubble and mortar used in the original apparatus. The apparatus was constructed as a physical and thermal match (Figure One). There was no requirement that the materials provide an aesthetic match.

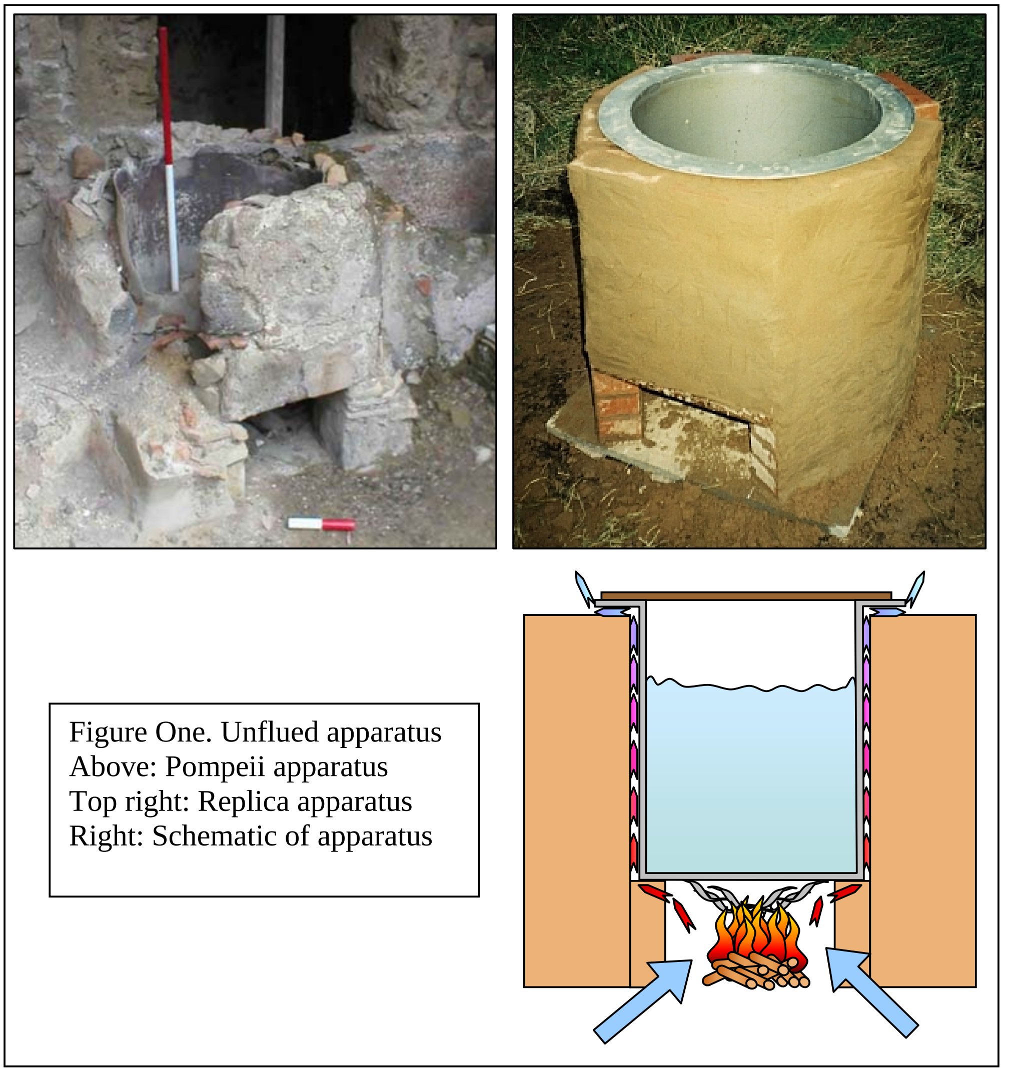

Figure One. Unflued apparatus
Above: Pompeii apparatus
Top right: Replica apparatus
Right: Schematic of apparatus

Experiment One

Although kettles and braziers of differing sizes and shapes had been discovered in Pompeii, no lid had not been discovered with them. It was presumed that this meant that dyeing had taken place without a lid. This was further enforced by the depiction on the gravestone of a dyer in southern France: he is stirring the kettle and no lid is shown. However, the depiction shows an action that cannot happen with a lid in place. If the lid had been made from an organic material then as it deteriorated it would have been burnt (free fuel) and replaced and the final lid would have been destroyed during the eruption. It is possible that inorganic lids were used, but there is no report of these having been found, or even something that could have been used as a lid that was mis-identified and discovered in the dyeing workshop. It has therefore been concluded that no lid was used.

The first experiment was to discover whether a lid had been used. It was speculated by both the archaeologists with dyeing experience and the engineers involved in the project that it was unlikely that the apparatus had been used without a lid: the archaeologists felt that the water loss through evaporation would be too great, the engineers felt that the apparatus would have been so inefficient that the Romans would have always used a lid. It was shown on use that without a lid the apparatus lost 14 litres of water, a sufficient depth to cause the ruination of the fleece. It was calculated that a lid of 20mm thick plywood would not only prevent a considerable amount of water evaporating but would also halve the heat lost through the top of the apparatus through evaporation. It was decided that such a lid should be used in future experiments (Figure Two). This was part of the original aim of the experiment: to determine if any parts of the apparatus were missing and that what had been reconstructed as the original design of an apparatus was actually viable.

Figure Two. Replica without and with lid. The lid was used in further experiments.

Experiment Two

The recipe used in these experiments was determined through laboratory work undertaken in 1999. A number of recipes using techniques and equipment appropriate to pre-industrial dyeing were consulted and found to differ greatly. These were then further examined and dissected. It was discovered that although the times stated in the recipes differed, the changes that were intended to be caused at each stage were the same. The recipes were then combined to provide a single one that would allow each change to take place in the shortest or most reasonable time (Hopkins, 2007). This stated that the water and dye should be heated to just below boiling, the fleece should be added and simmered in the dye, again below boiling, and that the fleece should be allowed to rest in the dye as it cooled to allow the dye to become fast and prevent the wool from matting.

Once the design had been shown to be viable and missing parts (the lid) added, it was possible to use the apparatus to mimic a dyeing cycle. The aim of Experiment Two was to determine the cycle-time and fuel requirement of dyeing with the apparatus. This included the time taken to heat the water, the time taken to simmer the dye liquor and the time taken to cool naturally. It was shown that despite charcoal being the higher calorific fuel (Goodger, 1980), wood was the fuel used in dyeing (Hopkins, 2005). There was insufficient air-flow to cause complete combustion of the charcoal. The apparatus had a 130 litre kettle containing 90 litres of water and upon reaching 95^{o}C a 2kg fleece was added. The water took 1.5 hours to heat to 95^{o}C, the recipe stated that the fleece should be simmered below boiling for 1.5 hours, and then the apparatus took at least 8 hours to cool naturally. This was a replica of one of the smaller apparatus from Pompeii: it may be presumed that the 900 litres apparatus would have taken longer to cool. From this it was calculated that dyeing could only have taken place once a day as the length of time taken to cool would not have allowed a second cycle. It was concluded that the apparatus was emptied and cleaned in the morning, heated during the day and left to cool overnight. To heat the apparatus and keep the water simmering at c95^{o}C took c126195 kJ of fuel which equated to 8kg of pine. This is not to say that the Romans used pine: what was important was to work out the calorific requirement. The actual fuel used may be substituted later.

Experiment Three

Following use of the apparatus the original apparatus in Pompeii were re-surveyed. This was the first survey undertaken with a practical knowledge of the apparatus and an understanding of its requirements. It is the most comprehensive survey to date. Each apparatus was assessed using Clarke’s polythetic entities, that is a list of criteria that each apparatus must possess to be an apparatus (Hopkins 2007, 2008 after Clarke 1976). Each apparatus was also assessed ergonomically. Each of the apparatus were demonstrated to have been of a viable design in their unconserved state, except for one identified by Moeller and discounted in this survey.

It was noted during the survey that there were two basic designs of apparatus: with or without a flue (Figure Three). The flue was an integral part of the apparatus that possessed one and did not appear to be an additional afterthought. The aim of the third experiment was to see what difference, if any, adding a flue to the apparatus would make. It was discovered that the quantity of fuel used and the time taken to heat and cool the apparatus were the same. However, the flame was far more controllable and less smoke was expelled from the front of the firebox. The flued apparatus were found in enclosed workshops and so it was suggested that they aided ventilation and complete combustion by helping to draw air through the firebox during heating.

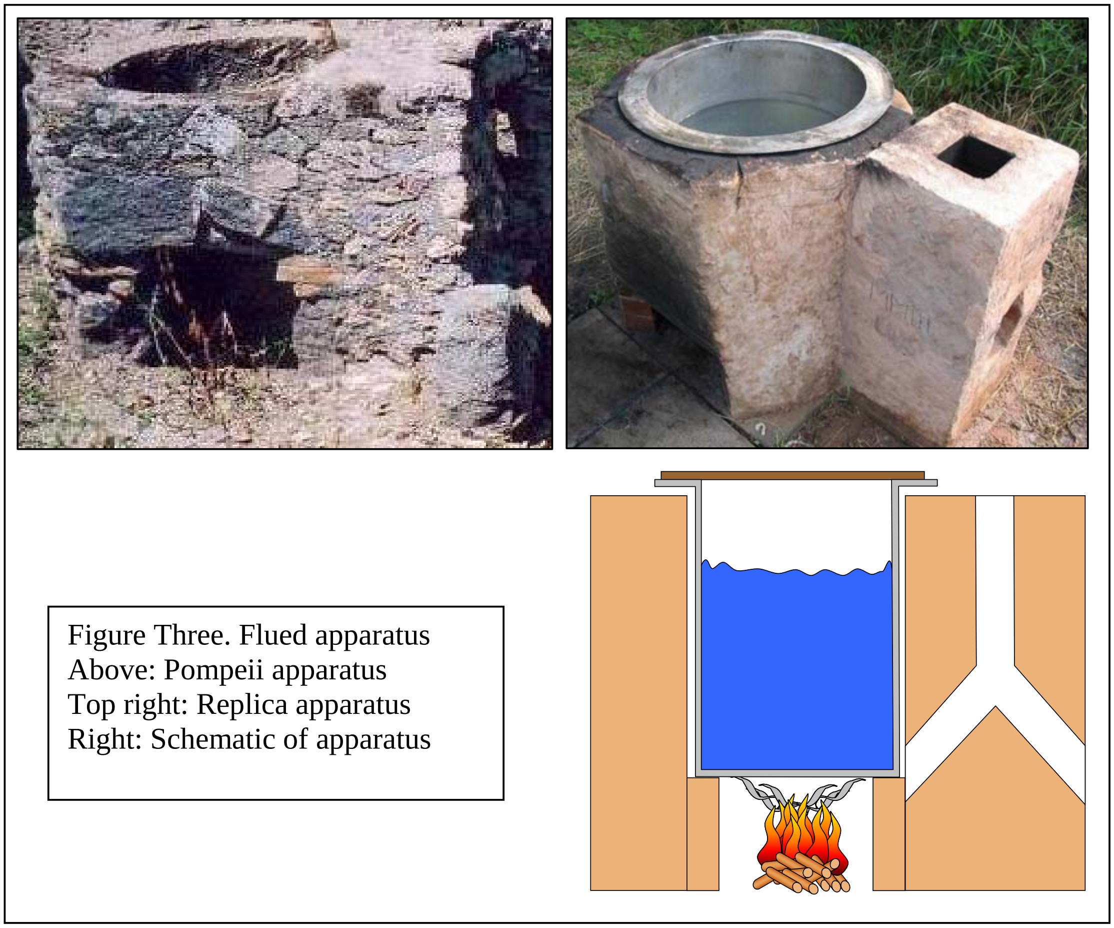

Figure Three. Flued apparatus
Above: Pompeii apparatus
Top right: Replica apparatus
Right: Schematic of apparatus

<u>Experiment Four</u>

> "The temptation, when a problem arose, was always to reach for the volume of Vitruvius, conveniently to hand, rather than go to the site, often inconveniently distant, to look at the actual remains, much less, to cross the quad to that, psychologically at least, even more distant ultima Thule, the Faculty of Engineering". A. Trevor-Hodge, 1992.

The study had begun in Archaeology and branched into Engineering. However, as the study grew increasingly scientific it was realised that the questions that would really allow an understanding of the apparatus, what happened during its heating and how this would impact its output, could only be answered in Engineering. Thereafter the study relocated to the School of Engineering with a branch in Archaeology. The data and approach continued the same but the means and method of answering the question suddenly widened.

To understand what occurred within an apparatus as it was heated it was necessary to record the temperatures of each part during the cycle. Experiment Four was a re-run of the dyeing cycle with six thermocouples in place to record the temperatures reached at varying points during the cycle. It was discovered that the temperature of the fire beneath the kettle was 600^{o}C. Although the water would have acted as a heatsink, drawing the heat away from the lead, the question was still raised of how the lead could support the weight of itself and the water while heated. There was disbelief that the original kettles had been constructed from lead as they should have had difficulty in supporting the weight without heating. To find that the fire reached over 300^{o}C above the melting temperature of lead added further intrigue.

That the kettle was constructed from lead had been noted in earlier studies but the importance of the choice of material hadn't been appreciated (Hopkins, 2008). The concentric circles in the base of the vat and the distended kettle in the corner of property VII xiv 17 showed that the kettle had been subject to creep. As the material was lead, a metal known to creep just in hot sunshine (Greenfield, 1972), it was suggested that creep could have played a far more important part in the failure and use of the apparatus than originally thought. It was therefore necessary to replicate the creep of the kettle to determine the speed of failure. It was noted that without knowing it Reynolds had been far more perceptive in his assertion that only the original materials should be used for a replica. He had stated that there could be qualities contained within an original material that while being unknown would still have an effect and it was necessary for these to be allowed for when constructing a replication. The stainless steel used had shared the same physical properties with lead except one, that is the two did not creep in the same way. To replicate creep in a lead kettle it was necessary to use a lead kettle, something that was banned for health and safety reasons.

Having moved department and studied the development in technology in the last thirty years it was noted that as one door closes another opens. While it wasn't possible to use lead due to new health and safety restrictions, it was now possible to replicate lead, to create a virtual simulation of the lead and its behaviour with the use of computer modelling. The apparatus could be recreated within a computer using Finite Element Analysis, that is breaking the apparatus down into parts, finite elements, each represented by an equation and then applying a force or temperature to one place and watching the reaction spread through the model. This had additional advantages: the environment surrounding the apparatus could be controlled, the apparatus design or materials could be altered and it was no longer necessary to construct 40 apparatus to see how each one reacted. Furthermore time could be speeded up or slowed so that twenty years of wear could take place in a day or the point at which the kettle failed could be studied minutely. The time taken for the original kettle to fail was unknown and had it been possible to construct the lead kettle it would not have been possible to wait indefinitely for it to fail.

Finite Element Analysis Results

The data required for the characteristics of lead that could be input into the FEA programme had to be defined during this project. This was done through use of the empirical creep strain-time data derived by Sahota and Riddington (2000). The use of FEA in testing the fatigue and failure of metals has been proven over decades as it is for example the means by which aircraft wings are tested. The results of this replication were unforeseen and groundbreaking. The lead didn't fail. Loading with water and heating over the first hour caused the kettle to bow slightly and at the end of heating the lead bowed under the weight until it was just above the base of the firebox. By the end of the second heating the lead was resting on the base of the firebox (Figure Four). But after six months although the lead had thinned it had not sheared. It was therefore concluded that breakage of the kettle was not a factor in the down-time of the process and that the kettle was amended after heating to allow its continued use.

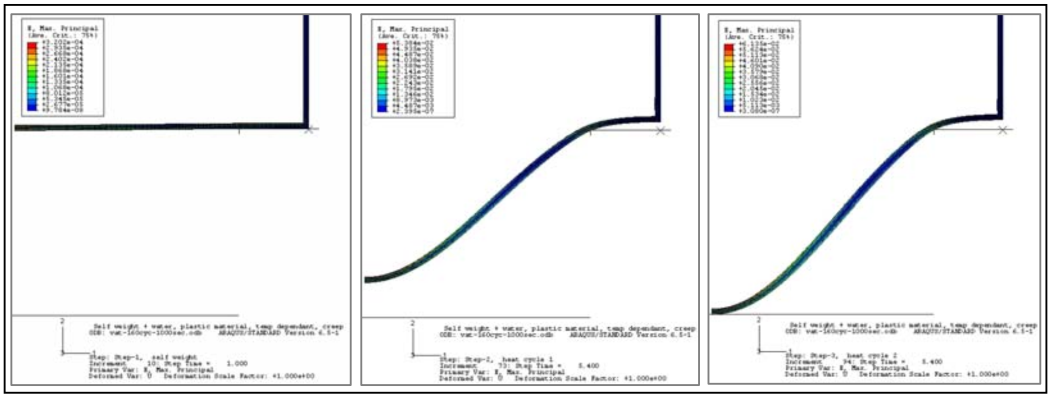

Figure Four. Left-right: The base of the apparatus after initial heating, at the end of the first cycle, at the end of the second cycle. The kettle is symmetrical so the simulation was of one half of the cross-section (half of the base and wall).

Results

Many important new findings came from this study. The dyeing industry was smaller than originally thought and may have relied on imports. While it is true that not every piece of textile was dyed (e.g. Bender Jørgensen and Mannering, 2001; Cardon, 2001), the Romans did completely dye materials used in soft furnishings. When the quantity of wool required to make a blanket or cushions is considered it may be seen that the maximum output that allowed an annual average of 4kg of dyed textile per person would be quickly used up. The lead apparatus does not appear to fail despite repeated use. Further work would be required to calibrate the computer model and to see how the base of the apparatus could have been altered to allow continual re-use. This study undertook the most comprehensive survey of the dyeing remains of Pompeii. Not only were all of the apparatus and workshops measured and recorded, but they were also assessed in context. The dyeing apparatus were assessed in relation to each other and their place within the workshop. The space, amenities and location of the workshops were also assessed. It is now possible to examine further influences on the dyeing process and output.

Numerous disciplines have been combined to answer the question of the dyeing capacity of Pompeii. Each has been shown to be relevant and vital in answering the question. The use of some, such as ergonomics and the application of thermodynamic principles was new to the question. The use or nature of application of others such as Finite Element Analysis were new to archaeology – FEA had only been used once before and that was to explore one quality of a single, portable artefact of one material (Kilikoglou and Vekinis 2002), whereas here it was used to explore multiple qualities of an industrial artefact of several materials, over time. This study has proved the use of each of these new techniques in the archaeological context. Furthermore, as the study was sequential it has increased accessibility. It provides an illustrated example exploring each of these techniques in turn.

The study faced many challenges. The influence of modern health and safety regulations meant that the apparatus could not be constructed from the original materials. However, the material match was so close that this did not present a problem in constructing the replica apparatus and the advance of computer technology meant that a wholly new application could be used to explore virtually what could not be done physically. This proved beneficial as a virtual model has advantages over a physical one: it is possible to slow and speed time, to change materials, to actually capture the moment at which a change in the materials takes place. A physical model would not have allowed this.

Conclusion

The challenges that the study faced meant that in the end it was far broader and with a more solid foundation than was ever originally envisaged. The results are now supported by classics, experimental archaeology and the principles of mechanical engineering. Had the study remained stationary within one subject the findings could only have been supported by one subject. Instead the approach had to adapt to changes in circumstance and at each point had to maintain integrity and demonstrate the validity of the argument and methods. The findings and method were challenged throughout by different disciplines and the results now withstand far greater scrutiny and provide a solid foundation for further work.

For further explanation and detail please refer to Hopkins 2007.

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