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Reverse Engineering the Ceramic Cooking Pot: Cost and Performance Properties of Plain and Textured Vessels

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Ceramic cooking pots throughout the world vary in exterior surface treatment from smooth to roughly textured. An intriguing example of this variation occurred in the Puebloan region of the southwestern United States where cooking pots changed from scraped plain to highly textured, corrugated vessels between the seventh and eleventh centuries AD, and then reverted back to plain-surfaced by the fifteenth century. To investigate potential cost and performance differences between plain and corrugated cooking pots, a set of controlled experiments were performed, which document manufacturing costs, cooking effectiveness, and vessel durability. These experiments indicate that while corrugation may have increased manufacturing costs, neck corrugations improved vessel handling, upper body corrugations yielded greater control over cooking, and basal corrugations extended vessel use-life. Discerning the explanatory significance of these results for cooking pot change in the Southwest and elsewhere requires additional data on the contexts in which these pots were made and used.

KEY WORDS: reverse engineering; experimental archaeology; cooking pots; Puebloan southwest.

INTRODUCTION

Reverse engineering is the process of analyzing a technology to document how it was made and how it operates. It differs from normal or forward engineering, which employs engineering concepts and principles to design new technologies, in that reverse engineering works backwards from a final product to reconstruct the

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cost and performance properties of an existing technology through scientific experimentation and analysis. Although experimentation has been a part of archaeology for many years, it has never become a significant component of archaeological practice. Most experimental studies in archaeology either try to replicate the complexities of real life (e.g., Bell *et al.*, 1996; Cole, 1973; Reynolds, 1979), or isolate a small number of variables for controlled study under highly unrealistic laboratory conditions (e.g., Bronitsky and Hamer, 1986; Steponaitis, 1984; Tite *et al.*, 2001). Both of these experimental programs have generated useful insights, but neither has produced the kinds of results that compel archaeologists to grant experimentation a more central role. However, reverse engineering's combination of a focus on actual technologies and a reliance on controlled experimentation offers the potential to generate secure, scientific knowledge about the cost and functional performance properties of technologies that directly informs on how they performed in the past (e.g., Pierce, 1999; Schiffer *et al.*, 1994). Although the need for artifact performance information has been emphasized by behavioralist and evolutionary approaches in archaeology (e.g., Neff, 1992; O'Brien *et al.*, 1994; Pierce, 1998; Schiffer and Skibo, 1987, 1997), such fixed points of knowledge about the past provide empirical anchors that often prove useful regardless of one's approach to explanation.

To reverse engineer a given ancient technology, investigators must identify the specific products to be studied, document how the products were made, and determine the technology's cost and functional performance properties through experiments, which are usually performed with replicas. This study explores the problem of smooth and textured ceramic cooking pots because they represent common cooking pot variants or technical choices employed around the world. However, rather than examining all known smooth and textured variants or modern pots with no ancient correlate, I focus on a specific example of plain and corrugated cooking pots in the Puebloan Southwest (Fig. 1) as an aid in designing appropriate experiments. Despite the fact the this study deals with a specific example, many of the methods and results are applicable to the general problem of explaining variation and change in smooth and textured ceramic cooking pots worldwide.

THE PROBLEM

Ancient Puebloan cooking pot designs followed an intriguing history involving changes in exterior surface texturing, which has piqued archaeologists's curiosity for over 100 years (Gifford, 1978; Kidder, 1936; Pierce, 1999). As with most technological histories, the record of Puebloan cooking pot technology is intricate and varies, sometimes substantially, from one region of the northern Southwest to another. However, the purpose of this paper is not to explain these intricacies, but to provide some the knowledge needed to formulate such explanations. Consequently, a broad-brush overview of the history will suffice.

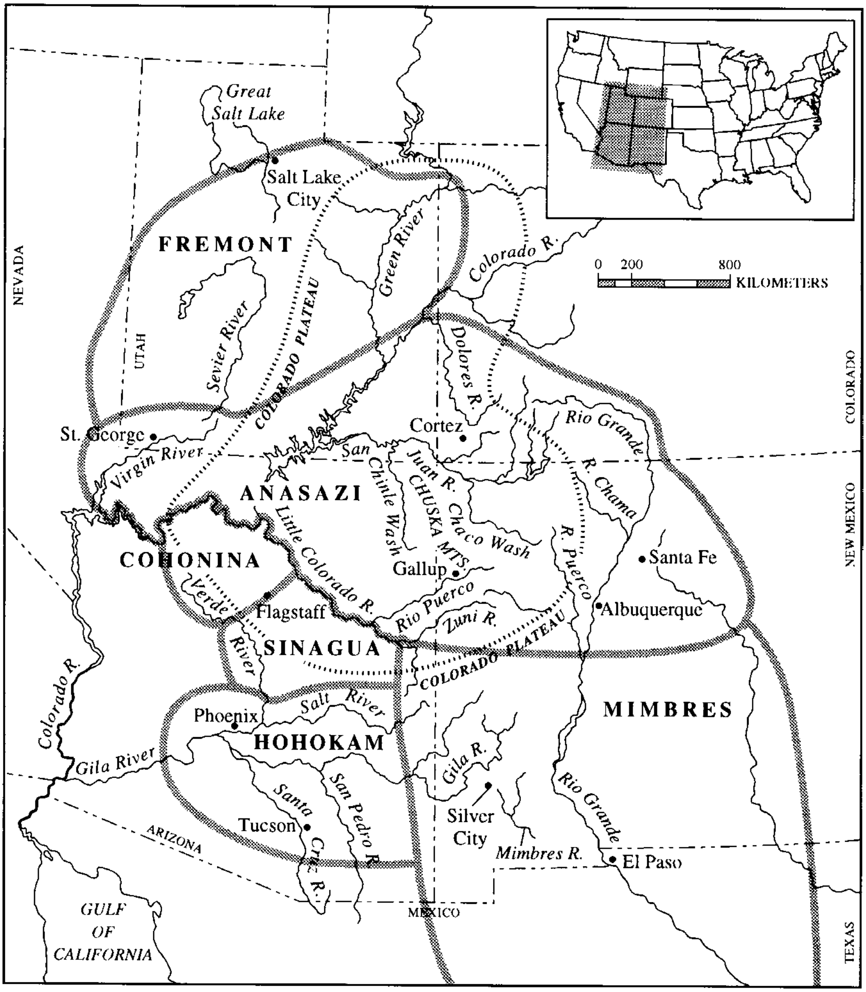

Fig. 1. Map of the southwestern United States.

Initially, ancient Pueblo potters made plain-surfaced cooking pots by scraping the surfaces of the vessels after coils or other construction elements were applied. During the eighth and ninth centuries AD, potters began leaving the exterior surface of some of the filleted, nonoverlapping or very slightly overlapping coils on the neck of vessels unobliterated, producing a neck-banded appearance (Breternitz *et al.*, 1974; Colton, 1955; Colton and Hargrave, 1937; LeBlanc, 1982; Pierce, 1999, in press). The next 200 years witnessed a great deal of elaboration and variation of neck-banding including the consistent overlapping of succeeding coils, the reduction of coil thickness, and the manipulation of coil surfaces and junctures by indenting and incising (Pierce, in press). In addition, the amount of the exterior surface of jars covered by exposed coils increased by spreading down to the upper and middle body portions of vessels.

During the early eleventh century, a single variant of exposed coils composed of substantially overlapped and indented coils and referred to as corrugation came to be used over the entire exterior surface of cooking pots producing a highly textured vessel surface. This corrugated cooking pot technology spread rapidly over a large part of the northern southwest (e.g., Breternitz, 1966; Breternitz *et al.*, 1974; Colton, 1955; Hays-Gilpin and van Hartesveldt, 1999; Hurst, 1991; Larson and Michaelson, 1990; Madson, 1986; Plog and Hantman, 1986; Pierce, 1999, in press; Reed *et al.*, 1996; Steward, 1936; Toll and McKenna, 1997). Corrugation remained the dominant cooking pot technology in much of the northern Southwest for the next 400 years, but was eventually replaced by scraped plain cooking pots during the fifteenth century (Kidder and Shepard, 1936; Spier, 1917). When the Spanish entered the Southwest during the sixteenth century, no trace of the corrugated cooking pot technology remained among the Pueblos they encountered.

Archaeologists have offered a variety of hypotheses to explain this dynamic history of Puebloan cooking pots. Many of these hypotheses identify possible performance differences between plain and corrugated cooking pots including manufacturing costs, cooking effectiveness, ease of handling, and vessel durability or use-life (e.g., Beals *et al.*, 1945, p. 140; Blinman, 1993; Gumerman, 1984, pp. 79–80; McGregor, 1941, p. 255; Schiffer *et al.*, 1994; Vivian, 1990, p. 146). However, none of these potential performance differences was identified by the kind of rigorous reverse engineering needed to document them adequately. This article presents the methods and results of a set of controlled experiments with plain and corrugated replicas designed to document selected cost and performance properties of these cooking pot technologies. The properties investigated include those identified above as having played a role in earlier attempts to explain changes in Puebloan cooking pot technology. By subjecting these properties of plain and corrugated cooking pots to a reverse engineering analysis, we can begin to evaluate their potential explanatory significance.

EXPERIMENTAL DESIGN

The experiments conducted for this study were designed to address three questions about plain and corrugated cooking pots: (1) Do they incur different manufacturing costs? (2) Is one technology a more effective cooking pot than the other? (3) Is there any difference in use-life or durability? Although insights to these questions can be gained by analyzing ancient pots and pottery fragments (Pierce, 1999), this study focuses on the use of controlled experimentation with modern replicas to reverse engineer plain and corrugated cooking pots.

Production of Replicas for Experiments

To perform these experiments, I needed to manufacture and use reasonably accurate replicas of the ancient cooking pots. These are not meant to be exact copies of particular ancient pots, but replicas that approximate ancient pots with regard to the particular features relevant to this study including basic construction technique, raw material, and size.

A total of 24 vessels, 12 plain and 12 corrugated, were made and individually numbered. In designing these replicas, I wanted to hold everything constant except those aspects of forming techniques that differentiate the ancient plain and corrugated pots. Thus, all pots were made from the same batch of raw materials, in the same size and shape (to the extent possible with hand-made items), formed by the same person, and fired together in the same kiln. Table I summarizes the dimensional data for the plain and corrugated vessels produced.

The raw materials consist of native clay from a Dakota Formation source located in southwestern Colorado (referred to as “Industrial Park Gray”) mixed with 15% by volume of crushed igneous rock collected from a quarry on the north side of Ute Mountain. Although southwestern cooking pots were made from a wide variety of clay and temper raw materials, this study focuses on the effects of surface texturing, not raw materials, on vessel performance. Given that no association between raw material selection and surface texturing has been documented in the southwestern archaeological record, I chose to standardize the raw materials by using a single clay, which is widely available in the northern southwest, and a temper commonly seen in ancient Southwestern utility wares.

The moistened clay/temper mixture was divided into 800-g portions for making each vessel. When the vessel was complete, the remaining clay was weighed to determine the weight of moist clay used to construct each vessel. During forming of the replicas, vessel size and shape were controlled by constant matching with a template designed to yield a finished, fired vessel that is 15-cm high with a globular, wide-mouthed, slightly flaring jar form (Figs. 2 and 3). I selected this form because it matches the shape of late neck-banded and early-corrugated vessels from the northern Southwest. Clint Swink, an experienced replicator of ancient pueblo pottery (Swink, 2004), formed all of the vessels.

I designed the replicas to differ in construction based on knowledge gained from analyses of plain and corrugated pottery assemblages from the Mesa Verde

Table I. Measurements of Replica Vessels Used in Experiments

Vessel type	Fired weight (g)	Vessel height (mm)	Maximum diameter (mm)	Total volume (mL)	Upper wall thickness (mm)	Base wall thickness (mm)
Corrugated	566.6 ± 37.4	153.8 ± 2.5	131.2 ± 4.0	1207.9 ± 55.0	5.7 ± 0.5	6.1 ± 0.6
Plain	510.3 ± 27.6	153.5 ± 3.7	130.0 ± 3.7	1207.5 ± 74.8	5.3 ± 0.6	5.1 ± 0.6

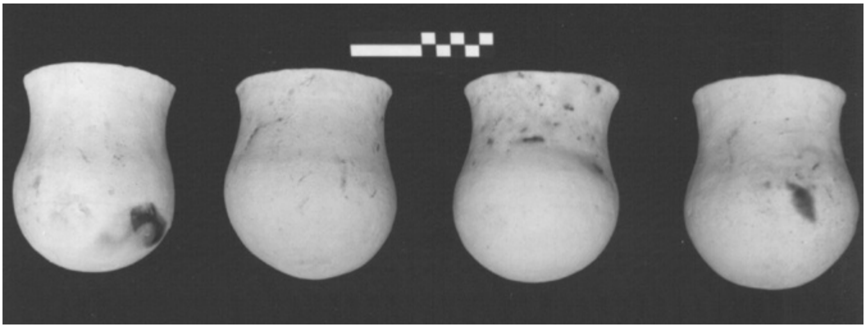

Fig. 2. Examples of fired replica plain vessels used in experiments.

region of southwestern Colorado (Pierce, 1999, in press). The plain vessels are replicas of the earliest cooking pots referred to as Chapin Gray. This variety of early gray ware vessel was made using relatively large coils, which were filleted or stacked on top of one-another to build up the vessel wall, and both surfaces were scraped smooth to weld coils together and form the finished shape (Pierce, 1999). The corrugated replicas were designed to match corrugated vessels produced during the eleventh century AD. The average values for amount of coil overlap (60%), spacing of indentations (11 mm), exposed coil height (6 mm), and wall thickness (5.5 mm) were used to guide forming of the corrugated pots. The corrugated vessels were built up from the base by first applying a coil in a spiral fashion over the base of an upside down vessel or *puki*. Once applied, these initial coils were indented with finger pressure, and the incomplete vessel was removed from the *puki* so that the interior surface could be smoothed by scraping. When this base portion had dried enough to support the weight of additional coils, new coils were applied to complete the jar form. Each added coil was indented with finger pressure after it was applied to the vessel and the interior surface was scraped smooth.

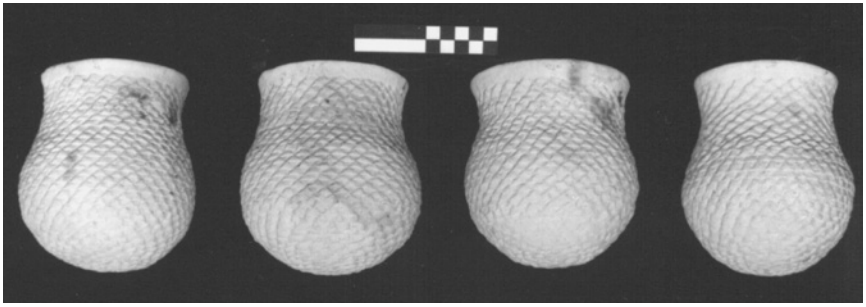

Fig. 3. Examples of fired replica corrugated vessels used in experiments.

After forming and air-drying, the replicas were further dried in a conventional oven overnight at 65°C. The day after oven drying, we fired all of the vessels in a replica of an ancient Mesa Verde region trench kiln. The kiln design and firing procedures were also the result of a reverse engineering analysis focused on the successful firing of organic painted black-on-white pottery (Blinman and Swink, 1997; Ermigiotti, 1997, Swink, 1993, 2004). First, we burned local pinyon and juniper wood to create a thick bed of coals in the bottom of the slab-lined pit kiln, and then partially covered these coals with additional sandstone slabs. We then arranged the 24 replicas systematically on top of these slabs so that plain and corrugated vessels were evenly distributed around the kiln. The vessels were then covered with a second layer of fuel, which was ignited from the top. Multiple type-K thermocouples placed among the pots measured the temperature profile of the kiln during firing (Fig. 4). Within 30–40 min after lighting of the secondary fuel layer, temperatures throughout the kiln had stabilized at about 800°C. The pots were exposed to this peak temperature for approximately 50 min, and then the entire kiln was smothered with earth and allowed to cool over night. Although the temperatures within the kiln were fairly consistent during the firing, the atmosphere varied slightly with some vessels showing slightly more oxidation or reduction than others.

Manufacturing Costs

Manufacturing costs for plain and corrugated vessels could have varied in the amount of time required to form the vessels and through differential failure

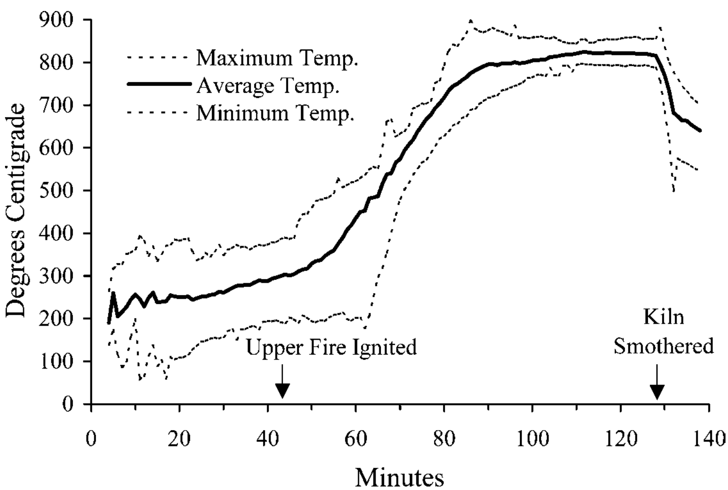

Fig. 4. Temperature profile within kiln used to fire replica vessels used in experiments.

rates during production. Regarding forming costs, archaeologists and potters have generally assumed that corrugated pottery is more technically demanding and consequently more costly to produce (e.g., Gifford, 1978; Shepard, 1939, p. 279). However, Blinman (Blinman, 1993; Blinman, personal communication, 2005) proposes that, all else being equal, corrugated pots are less costly to make. He suggests that it takes about one third the amount of time to form a corrugated vessel than a scraped plain vessel of a similar size, shape, and coil diameter because scraping involves an additional step in the forming process. Although the impact of production failures on manufacture costs of plain and corrugated pottery has rarely been considered explicitly, it is commonly believed that leaving coils exposed reduces the strength of the weld between coils. If true, this could increase the frequency of structural failures during drying and firing (Blinman, 1993; Schiffer *et al.*, 1994). However, others have suggested that the use of overlapping and indenting of coils may have strengthened coil welds (Beals *et al.*, 1945, p. 140).

Measurements and observations made during the replication of plain and corrugated vessels are used to document manufacturing costs for this study. I measured two kinds of cost: forming time and vessel-production failures. To measure differences in costs accrued during the forming stage of manufacture, I recorded the time required to form each of the 24 replica vessels prepared for this study. I focused on forming time because the time required for other stages of the manufacturing process, such as clay preparation and drying times, depend on several factors that are irrelevant to this study. Failure of vessels during manufacture is most likely to occur during the drying and firing stages because of the shrinkage of the clay body that occurs during each of these steps. After both drying and firing the replicas, I visually examined each of the 24 vessels made for this study for the development of any flaws or failures.

Cooking Effectiveness

The changes in Puebloan utility wares from plain to corrugated and back to plain vessels occurred mainly in cooking pots. This inference is based on a wide variety of evidence including the restriction of vessel forms to wide-mouth jars, the common occurrence of soot adhering to the exterior surface in a spatial pattern produced of a pot sitting upright on a wood fire, and the frequent presence of interior surface alterations and residues indicative of the vessel's contents being exposed to heat (Pierce, 1999). Consequently, differences between plain and corrugated vessels in the transfer of heat through the vessel wall, and the effects of these differences on the contents being cooked constitute relevant measures of performance. For many years, archaeologists have asserted that the greater exterior surface area of corrugated vessels would have resulted in more effective heat transfer between the heat source and the vessel contents, and that this difference may have played a significant role in the adoption of corrugation (Gumerman, 1984, pp. 79–80; McGregor, 1941; Rice, 1987, p. 232; Vivian, 1990, p. 146). However, experiments by Plog (1986), Schiffer (1990), and Young and Stone (1990) designed to measure the effects of various surface treatments, including exterior surface texturing, on heating effectiveness suggest that corrugation does not necessarily improve performance, and can even degrade it. Although intriguing, these experiments have not been conclusive mainly because of problems seen with the design of the experiments. For example, the vessels used were not accurate replicas in terms of the raw materials, forming techniques, vessel morphology, or firing regimes employed, and the number of tests, or experimental runs, was extremely low.

To more thoroughly evaluate the heating effectiveness of plain and corrugated gray ware pottery, I used the 24 replicas described above in cooking experiments. These experiments were designed to assess the impacts of three factors—exterior surface treatment, interior surface lining, and cooking contents. Each factor consists of two states. Exterior surface treatment includes scraped plain and corrugated. Interior surfaces are either unlined or lined with pinyon pitch. I chose to study the effects of interior surface lining because previous experiments had shown that reducing vessel wall permeability through lining could affect heat transfer effectiveness (Schiffer, 1990). Although there is no record of ancient Pueblo pottery being lined with pitch, this is a common practice with ceramic cooking pots in other parts of the world. In addition, I thought that pitch was probably one of the most effective lining materials available to ancient Pueblo potters, and I wanted to test the most extreme case. This assumption proved incorrect as I discuss in detail later. The contents of vessels varied by filling some with 700 mL of plain tap water and others with 700 mL of corn mush created from 600 mL of tap water mixed with 100 mL of chicken stock and 15 mL of corn meal. I included chicken stock to add fat to the contents and to simulate the addition of turkey or other meat to corn-based recipes. The three factors with two states each produce eight possible factor combinations. With 24 vessels, three vessels can represent each factor combination. I randomly selected which vessels would be assigned to each factor combination.

The experiment involved heating each filled pot on a propane burner set at the same output level so that the temperature at the base of the pot stayed at about 450°C. Once the heat was applied, I measured the time elapsed before a peak temperature of the vessel contents was reached, which was boiling (~95°C because of high elevation) in most cases. Before filling the pots for each run of the experiment, they were weighed to the nearest 1/100 of a gram. After weighing, the pots were placed on the burners, and filled with the appropriate contents. We then arranged all of the temperature probes and began logging temperature data. Temperatures were measured by placing the tips of stiff, submersible, type *k* thermocouple probes against the exterior surface of the vessel at three points (base, middle body, and neck) and one probe inserted into the contents of the vessel 1 cm above the base of the pot (Fig. 5). After initiation of temperature recording,

Fig. 5. Arrangement of vessels and temperature probes during cooking effectiveness and use-life experiments.

the burners were ignited and adjusted to the appropriate level. I selected 450°C as the target flame temperature because open wood fires can easily reach that temperature. However, it was often difficult to set and hold the temperatures of the propane burners resulting in temperatures at the base of the pots fluctuating between 400°C and 500°C. This range is still well within that of open wood fires. The time elapsed between filling the pots and igniting the burners was usually less than 3 min.

The filled pots were heated for 40 min and then allowed to cool for 20 min, recording temperatures for the entire hour. After the cool down period, I emptied the vessel contents into a graduated beaker to measure remaining volume, the interior surface was rapidly wiped with paper towel, and the pot was weighed again to the nearest 1/100 of a gram. The temperature data for each vessel were logged every 10 s by computer for each experimental run. In addition to the temperature data, we also recorded observations of vessel performance during heating and cooling, such as boilovers, leaks, etc., and noted any alterations to the vessel surfaces and vessel integrity after the experiment. This experiment was repeated 12 times for each vessel resulting in 36 measurements for each factor combination. Because four burners were used in each run of this experiment, the pots were rotated to a new burner for each run so that each pot was heated three times on each burner. In addition, four plain and four corrugated vessels containing corn mush were used in numerous additional cooking runs as part of the use-life experiments discussed below. Data on heating effectiveness generated during these use-life experiments are incorporated into the evaluation of heating effectiveness where appropriate.

In addition to performing the cooking experiments, I measured the permeability of the wall of each pot before the first experimental run and after run numbers 4, 8, and 12 of each vessel. Wall permeability was measured by weighing the dry pot to the nearest 1/100 of a gram, and then filling the pot to the rim with tap water and letting the water soak into the vessel wall for 60 s. The water was then emptied and the inside surface wiped rapidly with a paper towel to remove any liquid remaining on the vessel surface. The empty pot was then weighed again to the nearest 1/100 of a gram. The difference between the two weights is a measure of the amount of water absorbed into the vessel wall during the soak period and thus reflects the permeability of the inside surface.

Vessel Durability

The amount of use obtained from a pot before physical failure or degraded performance requires replacement affects the cost of vessel technologies. The longer a vessel lasts during use, the lower the production costs, as fewer vessels need to be manufactured per unit of work performed. Two factors affect the durability of ceramic vessels: (1) the strength or resistance to failure of the material and formal properties of the vessels when exposed to stress; and (2) the likelihood that the vessels will experience significant stress during production and use.

Two kinds of stress—mechanical and thermal—operate to produce strains within the wall of a ceramic cooking pot. Both of these stresses can cause a vessel to fail through catastrophic cracking, or through fatigue produced by repeated exposure to subcritical stresses, which can eventually result in structural failure or significant performance degradation. Mechanical stress occurs when force is applied to the vessel through contact with another massive substance, usually a solid. The nature of the mechanical force(s) applied (whether static or dynamic, and their magnitude and direction) and the materials and forms involved determine, to a great extent, the nature of the resulting stresses and strains. Mechanical stresses frequently generated in ceramic pots during use include the more or less static forces exerted on the vessel wall by the contents of the vessel, and the dynamic forces of impact and abrasion such as those produced by impacts from stirring and serving utensils, by moving the vessel onto and off the fire, and perhaps by cleaning. These stresses are normally weak, and any vessel that survives forming, drying, and firing will probably withstand the routine mechanical stresses of use. Catastrophic impact, such as that produced by dropping a vessel or hitting it against something during transport, is the most likely mechanical stress to produce vessel failure.

Thermal stresses arise from temperature effects. Temperature gradients and the differential expansion of distinct materials exposed to the same heat within the vessel wall can produce stresses if some force constrains thermal expansion. Firing and use in cooking generates thermal stresses through transient temperature changes experienced in the vessel wall during heating and cooling, temperature gradients that exist between different portions of the vessel (for example, the difference between the heated exterior surface and the interior surface which is cooled by contact with the contents of the vessel), and differential thermal expansion of clay and temper constituents of the vessel. These thermal stresses can cause weakening and failure of the vessel wall through the initiation and propagation of cracks.

In contrast to the relatively weak mechanical stresses experienced during normal use, ceramic cooking pots are exposed to considerable, constant thermal stress during cooking. From the moment a pot is first placed on the fire until it has cooled after removal from the heat, a thermal gradient exists between the heated exterior surface and other cooler parts of the vessel. If the vessel is used to cook a liquid, the temperature of the interior surface will not exceed by much the maximum temperature of the contents. The temperature of the heated portion of the exterior surface can be substantially higher depending on the temperature and configuration of the heat source. With a vessel sitting directly on a normal wood fire, the temperature difference between exterior and interior surfaces at the base of the pot can easily range between 300°C and 600°C. The thermal gradient produced by this temperature difference results in greater thermal expansion of the heated exterior surface than the cooler interior surface. In addition, the thermal gradient up the vessel wall from the heated base to the unheated upper body results in greater expansion of the lower part of the vessel relative to the upper part. Under these conditions, the cooler inside surface acts as a restraining force to the vertical and horizontal expansion of the exterior surface resulting in compressional stresses at the exterior surface of the vessel wall, tensional stresses at the interior surface, and shear stresses vertically within the wall (Kingery, 1955). No radial stresses develop because no resistance exists to radial expansion.

Several studies have documented how a variety of material and formal design characteristics can improve the potential durability of ceramic cooking pots (e.g., Bronitsky and Hamer, 1986; Crandall and Ging, 1955; Feathers, 1989, 1990; Feathers and Scott, 1989; Hasselman, 1970; Kingery, 1955; Manson, 1966; Rye, 1981; Schiffer *et al.*, 1994; Skibo *et al.*, 1989; Steponaitis, 1984; Tite *et al.*, 2001; Wallace, 1989; West, 1992). This is done through either increasing resistance to stresses brought about by raising the critical level of stress needed to induce catastrophic failure and creating obstacles to crack propagation, or decreasing the magnitude of the stresses to which vessels are exposed. For example, thicker vessel walls are more resistant to mechanical stress, while using large, platy or fibrous temper improves thermal stress resistance by increasing the resistance to crack growth. Whereas certain formal properties, such as rounded shapes and contouring or thinning of vessel walls, can reduce thermal stresses and avoid stress concentrations. However, differential effects of given aspects of vessel design in the face of various kinds of stresses and strains create the potential for design trade-offs, and suggest that there is no single design choice that can maximize durability in the face of all potential stresses.

We can see this potential for design trade-offs manifest in Southwestern plain and corrugated cooking pots. Plain vessels may be stronger than corrugated because poorly joined coils in corrugated pots constitute potential zones of weakness and stress concentration that can crack more easily during drying, firing, and use (Manson, 1966, pp. 250–253, 385–391; Smith and Smith, 1960; Stokes, 1968). However, this potential strength difference is mainly in the face of mechanical stress, not the thermal stresses generated during firing and use in cooking. Experiments by Schiffer *et al.* (1994) suggest that ceramic vessels with deeply textured exterior surfaces may be less susceptible to failure (cracking and surface spalling) due to thermal stress than vessels with plain exterior surfaces. The textured surface of corrugated pottery may also reduce the likelihood of catastrophic impacts brought about by dropping vessels as the rough surface may improve the graspability or ease of handling of the vessels (Blinman, 1993; Schiffer *et al.*, 1994).

To assess the impacts on vessel durability and potential use-life of design choices actually made by ancient Pueblo potters, I conducted a set of strength and use-life experiments on a subset of the plain and corrugated vessels employed in the study of manufacture costs and cooking effectiveness. The use-life experiments were designed to assess the responses of plain and corrugated vessels to both mechanical and thermal stresses. In addition, I recorded observations on my experiences in handling the vessels throughout the cooking effectiveness and use-life experiments to generate quantitative and qualitative data on the potential differences in the ease of handling between plain and corrugated vessels.

Mechanical Stress

To document how plain and corrugated vessels respond to mechanical stresses, I measured the strength of four of the plain and four of the corrugated replicas. Each of these vessels had been used for a total of 8 h during the cooking effectiveness experiments. This very short duration of use would have produced little or no strength degradation from the unused state. I employed three different strength measurement techniques, a falling-weight impact test (Mabry *et al.*, 1988), a pendulum impact test, and a ball-on-three-ball biaxial flexure test (Neupert, 1994).

In the falling-weight impact test, I set the rim of each vessel on a platform of wet clay arranged so that the falling weight, a 66.7 g steel ball bearing, would strike the center of the base. The first drop of the weight was from 40 cm above the base of the vessel, and the drop height was increased by one cm for each subsequent drop until the vessel failed. Failure in this experiment is defined as a fracture extending all the way through the vessel wall leaving the vessel incapable of holding a liquid.

The pendulum impact test was designed to measure the strength of vessels that were still intact after the falling-weight test except for a small hole in the base produced by the falling-weight impacts. To conduct this test, I suspended the vessels by a string tied around the vessel neck and centered over the vessel mouth. The other end of the string was fastened to an armature set far enough away from a concrete pillar so that the pot would just touch the pillar when suspended freely. The test involved pulling the vessels away from the pillar while maintaining tension on the string, and releasing the pots so that they would swing into the concrete pillar. This was done several times for each vessel from increasingly greater release angles until the pots failed completely. The first drop angle was 10° and I increased the angle by 5° increments. During both the falling-weight and pendulum impact tests, I kept notes on the responses to impact displayed by each vessel.

The biaxial flexure test was performed on fragments cut with a rock saw from the upper body and base of each of the plain and corrugated vessels included in the use-life experiments. The strength of these pieces, cut to roughly 2 cm × 2 cm, was measured by breaking them in a compression cage using the ball-on-three-ball biaxial flexure test described by Neupert (1994). In this test, the sherd is placed horizontally, concave surface down, over three balls equally spaced around a 1.27-cm radius circle and a fourth ball applies a load at 0.25 mm/s onto the upper surface of the sherd at the center of the circle. When the sherd breaks, a peak load indicator shows the maximum load applied at failure. I then converted the peak load values to a modulus of rupture (MOR) using the formula presented by Neupert (1994), which standardizes the load data for differences in wall thickness.

Thermal Stress

As mentioned above, cooking produces three principal kinds of thermal stresses within the wall of a vessel: compressional stress at the exterior surface; tensional stress at the interior surface; and shear stress within the vessel wall. The tensional and shear stresses are the most potentially damaging because ceramic materials are relatively weak in the face of these stresses while relatively strong with regard to compressional stress (Grimshaw, 1971). These tensional and shear stresses arise from the differential expansion of the hotter, lower, exterior portion of the vessel relative to the cooler, interior and upper body portions. The period of peak stress in a vessel used for cooking occurs during initial exposure to heat when thermal gradients are most extreme. Heating of the contents reduces the thermal gradient through the wall somewhat, but because the peak temperature of food mixed with water is relatively low (∼100°C), fairly intense thermal gradients, and thus thermal stresses, continue throughout the duration of the cooking episode.

To measure the responses of plain and corrugated pottery to prolonged exposure to thermal stress, I selected eight vessels (four plain and four corrugated) from among the replicas used to cook mush in the heating effectiveness experiments, and used these vessels for extended periods. The experimental protocol was the same as the heating effectiveness experiments except cooking continued for several hours at a time, and consequently, more water had to be added periodically so the vessels did not cook dry. Temperature data were only recorded until the contents of each pot had boiled. After each day of cooking, I examined the pots visually, and carefully squeezed, poked, and tapped them to expose any degradation such as cracks, spalls, and pits. Periodically during the use-life experimental runs, I performed the same vessel wall permeability measurements as I had during the cooking effectiveness experiments.

The goal of the experiment was to cook in all eight pots until they failed resulting in an average use-life estimate for each vessel type. However, after a little more than 600 h of cooking in one set of four pots and 300 h of cooking in the other set, only two vessels had failed. Consequently, I decided to forgo using each vessel until it failed. Instead, I attempted to gauge potential use-life differences by observing the development of flaws and failures during use, measuring the residual strength of the intact vessels with impact and biaxial flexure tests, and tracking changes in heating effectiveness over the course of the experiments.

RESULTS

This presentation of the results of the reverse engineering analyses is organized into five main sections. It begins with the results of the manufacturing cost experiments, which is followed by presentations on cooking effectiveness, and three sections on vessel durability covering the responses to mechanical and thermal stresses and observations regarding differences in the ease of handling plain and corrugated vessels.

Manufacturing Costs

Forming Time

As described above, I measured the time required to form each of the 24 replica vessels prepared for this study. Two factors can significantly affect the validity and reliability of these forming time measurements. First, the values are useful only if the potter is proficient in forming the vessels and enough vessels have been formed at a proficient level to yield an accurate estimate of forming time. Comparing vessel-forming times over the sequence of construction episodes from the first vessel to the last can be used to assess replicator proficiency. At the outset, forming times may be high, but as the potter's proficiency improves, forming times should decrease until maximum proficiency is attained and forming

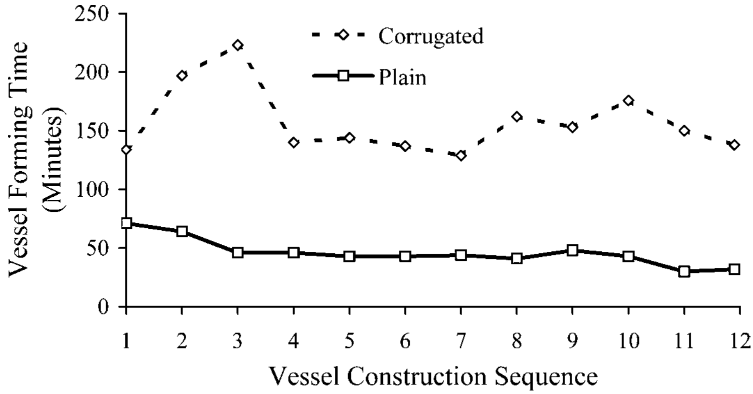

Fig. 6. Vessel forming times arranged by sequence of construction for the 12 plain and 12 corrugated replicas.

times stabilize with only small random fluctuations. It is only after the values have stabilized that forming time measurements are useful for estimating manufacture costs.

Figure 6 shows the sequence of forming times for the plain and corrugated vessels manufactured for this study. Both sets show a slight trend toward decreased forming time through the entire sequence of 12 vessels, but values are more stable after two plain and three corrugated vessels were manufactured. In neither case is there a large decrease in forming times. This may result from the considerable experience Clint Swink, the potter, had with forming plain and corrugated vessels before the experiment began. In fact, it is possible that both sequences show mostly random fluctuations.

Second, the validity of forming time measurements requires that the techniques employed to form the vessels match as closely as possible those used by the ancient potters. The techniques used for forming the plain and corrugated replicas for this study were selected after examination of forming traces in pottery analyzed from the several well-dated utility ware assemblages from the Mesa Verde region of southwestern Colorado (see Pierce, 1999, in press), and experimenting with techniques to produce pottery with the same characteristics. However, it is possible that multiple techniques can produce the same results, and that the techniques employed to make the replicas differ from those used by the ancient Pueblo potters. In addition, corrugated pottery from elsewhere in the Southwest indicate that a variety of techniques were used to form corrugated vessels. Although more detailed observations of the ancient pottery can improve our understanding of construction techniques, it is likely that we will never know with certainty what set of techniques were actually used in the past. Given that the best we can say about the forming techniques employed for this study is that they are reasonable

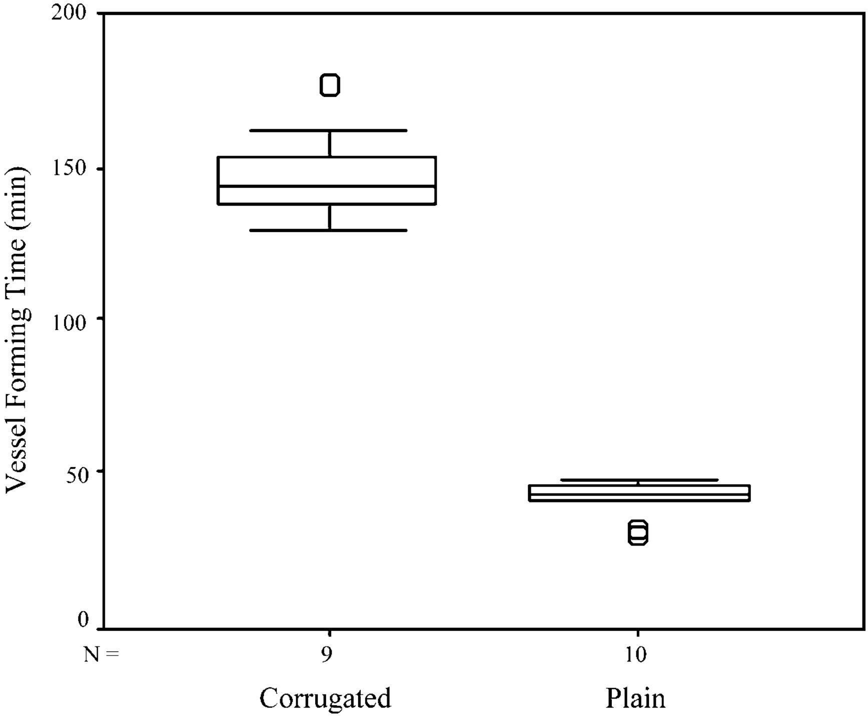

Fig. 7. Box plot of time needed to form replicas of plain and corrugated vessels after forming times stabilized.

approximations of those used in the past, we should avoid using the forming time results as more than a relative measure of manufacture costs.

My forming time experiments produced the opposite result of Blinman's (1993) replication experiments. In the experiments performed for this study, corrugated pots took an average of three times longer to form than the plain vessels (Fig. 7) rather than the one third less time observed by Blinman. This fairly major difference probably results from the use of different forming techniques, an issue addressed in more detail in the discussion section below.

Production Failure Rates

No flaws were detected after drying, but two vessels, both with plain surfaces, developed cracks during firing. One vessel sustained a rim crack that extended 2.7 cm down from the rim while the other vessel developed a 3.6-cm long crack parallel to the rim at the base of the neck. This latter crack may have followed a join between coils. Although water seeped from both of these cracks, neither compromised the use of the vessel nor did the cracks expand during use.

In various pottery replication and firing experiments performed during the 1990s, I and other pottery replicators have observed that in vessels with corrugated necks, cracks propagating down from the rim tend to stop at the first exposed coil junction below the rim. In addition, Eric Blinman (personal communication, 2005) notes: "I have never lost a corrugated exterior vessel (gray or white ware) to heat spalling during firing, while I have lost plain surfaced vessels of all wares." Based on this anecdotal evidence, it appears that corrugated vessels may be more resistant to the stresses generated during manufacture, and thus may fail less often. However, it is unclear whether the difference is sufficiently great to affect production costs.

Cooking Effectiveness

Heat Transfer

Box and whiskers plots of the time required for vessel contents to reach peak temperature for each of the eight factor combinations (Fig. 8) show considerable variation among vessels containing only water, and remarkable similarity among vessels cooking corn mush. Between both the plain and corrugated vessels containing water, the unlined vessels took longer to reach peak temperature than the vessels lined with pitch, and the unlined corrugated vessels were by far the least effective at heating the water. In addition to taking longer to heat, water in unlined corrugated vessels frequently failed to boil in the 40 min of heating time during each experimental run. This matches ethnographic observations of Kalinga cooking pots that had lost their resin lining (Skibo, 1992, p. 163). In contrast, no significant difference ($p < 0.001$) exists in the time required to reach peak temperature among the lined and unlined, plain and corrugated vessels in which we cooked corn mush, and the contents boiled vigorously in all cases.

These results support and extend those obtained by Young and Stone (1990) and Schiffer (1990), and compliments ethnographic observations by Sillar (2000, 2003). Reducing vessel wall permeability, either by applying a sealant before use or through cooking food, which is absorbed into and clogs pores in the vessel wall, greatly enhances heating effectiveness. Figure 9 shows the relationship between wall permeability (amount of absorbed water) and heating effectiveness (time to reach peak temperature) for plain and corrugated vessels. Each point in Fig. 9 represents data for an individual vessel averaged from all measurements made after the first run. I excluded data from the first run because wall permeability frequently changed notably after that run, a phenomenon I address separately below. Figure 9 shows that a strong, negative, relationship exists between heating

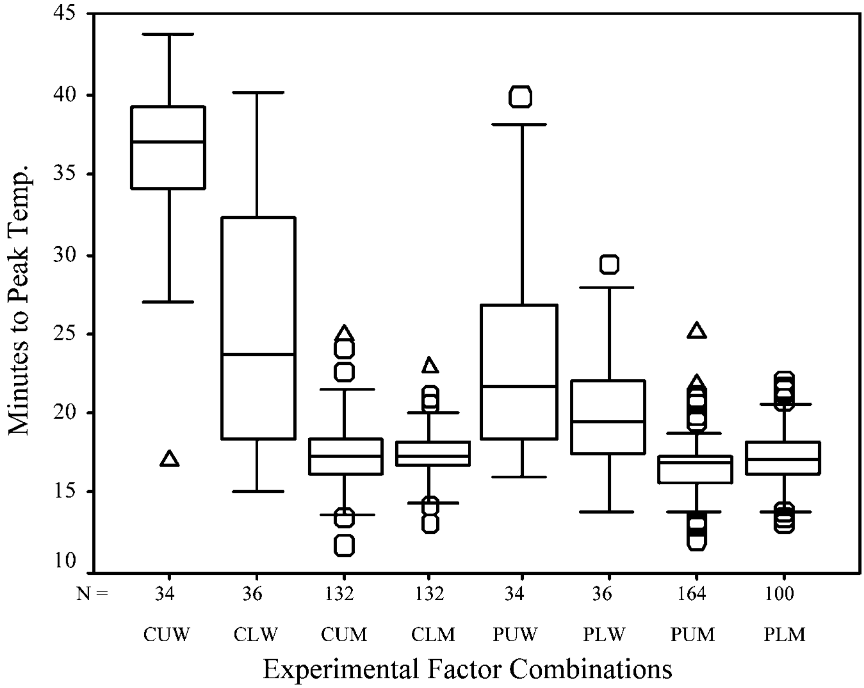

Fig. 8. Box plots of time elapsed before reaching peak temperature for multiple runs with vessels in each of the eight experimental factor combinations (C: corrugated, P: plain, L: lined, U: unlined, W: water contents, M: mush contents). N = number of runs.

effectiveness and wall permeability. As vessel wall permeability increases, heating effectiveness decreases.

However, the nature of this relationship differs between plain and corrugated vessels. For a given increase in vessel wall permeability, heating effectiveness degrades at a substantially greater rate for corrugated than for plain vessels. At low wall permeability, plain and corrugated vessels are very similar in heating effectiveness. At very high wall permeability, corrugated vessels are considerably less effective at heating their contents than plain vessels.

In addition, the wall-permeability–heating-effectiveness relationship is linear for plain vessels and slightly curvilinear for corrugated vessels. This difference derives from the degradation of the pitch lining over experimental runs. The time needed to reach peak temperature in the lined vessels heating water increased gradually during the course of the experiment. This is due to the loss of some pitch during each run making the vessel walls more permeable. Given the different responses to wall permeability between plain and corrugated vessels, the lined corrugated vessels heating water lost heating effectiveness more rapidly than the comparable plain vessels. This produced the curvilinear relationship for corrugated

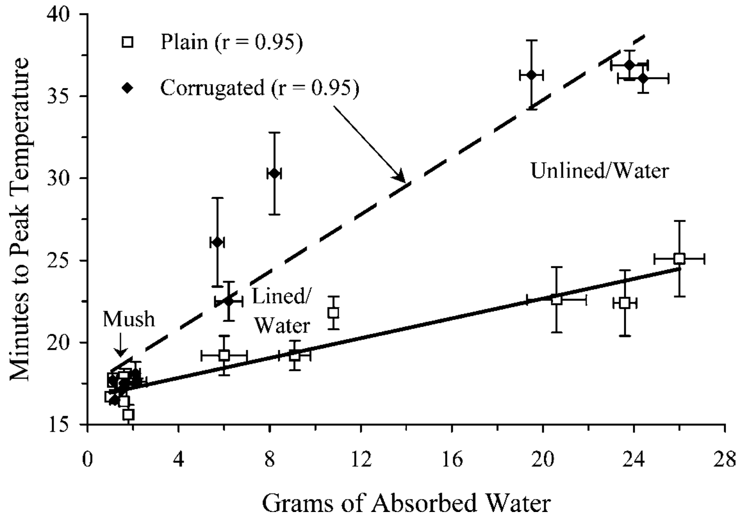

Fig. 9. Scatter plot of heating effectiveness and vessel wall permeability. Each point shows the mean value ± standard error of the mean for an individual vessel used in multiple experimental runs.

vessels. I suspect that the relationship would be linear if another more stable method of controlling wall permeability was used.

Changes in the time required to reach peak temperature over the course of the 12 experimental runs (Fig. 10), also expose important patterns in the relationship between wall permeability and heating effectiveness. In the first runs of each set, the contents (regardless of composition, water or mush) of corrugated vessels lined with pitch reached peak temperature more rapidly than in the pitch-lined plain vessels, while among unlined pots, the plain vessels heated their contents more rapidly. Degradation of the pitch lining through use resulted in a loss of heating effectiveness particularly for corrugated vessels heating water as noted above. For the lined vessels cooking mush, heating effectiveness diminished after the first run, but then stabilized as starch and other food particles permeated and lined the vessel walls.

Among the unlined vessels, the time to reach peak temperature in those heating water fluctuated randomly with the corrugated vessels consistently proving less effective than the plain vessels. For the unlined vessels cooking mush, the initial run required more time to reach peak temperature than subsequent runs. The heating effectiveness of these unlined vessels improved as the mush soaked into the vessel walls. Very small, yet consistent, differences in heating effectiveness between plain and corrugated vessels persist after the first run, with plain vessels remaining slightly more effective than corrugated vessels.

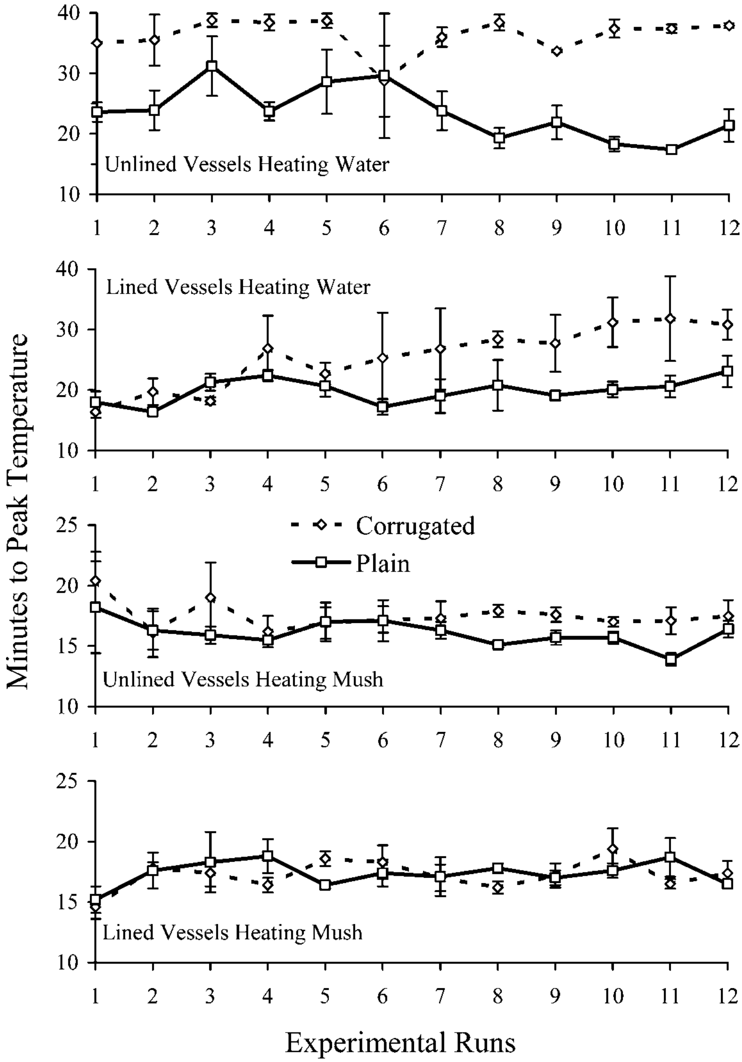

Fig. 10. Changes in heating effectiveness over experimental runs for different factor combinations. Error bars show the standard error of the mean temperature obtained from multiple measurements.

Cooking Control

In addition to heat transfer, the control of temperatures so that the contents cook but do not boil over has been shown ethnographically to be an important aspect of cooking pot performance, and can even supersede heat transfer effectiveness for some cooks (Skibo, 1994). During most of the heating effectiveness and use-life experimental runs, we monitored the occurrence and intensity (heavy or slight) of boilover episodes. For the cook, heavy boilovers present a problem because they can douse the cooking fire and waste food whereas slight boilovers waste little and usually evaporate before reaching the fire. No boilovers occurred in the vessels containing only water, but boilovers were common in the vessels cooking corn mush because the starch in the corn meal tends to froth when it boils. Out of the 140 experimental runs of plain and corrugated vessels cooking mush for which boilovers were recorded, heavy boilovers occurred in 48% of plain vessel runs and only 24% of corrugated vessel runs.

Vessel Durability: Responses to Mechanical Stress

This section presents the results of the three different strength tests: falling weight, pendulum, and biaxial flexure (Tables II and III). Of the eight vessels (four plain and four corrugated) used for a total of 8 h cooking, the falling weight test resulted in a small hole being driven through the base of the pot in seven cases. In one of the corrugated vessels, the impacts produced large cracks in the vessel wall rather than a small hole. This latter failure required substantially more impacts to produce than the small holes. Using the results from the seven comparable tests, the four plain vessels required an average of 10.25 impacts to fail with a standard deviation of 4.72 while the three corrugated vessels required an average of 12.67 impacts with a standard deviation of 4.16. Although the corrugated vessels tend to be slightly more resistant to the stresses of focused impact on the base, the difference is not significant at the 0.05 level, and thus may result from sampling error particularly given the very small sample size. Another factor that may account for the small difference in strength is the greater basal wall thickness of the corrugated vessels (see Table I).

The pendulum impact test was performed on the seven vessels (four plain and three corrugated) that did not fail by substantial cracking in the falling weight impact test. In the pendulum tests, the four plain vessels failed at an average drop angle of 36.25° with a standard deviation of 2.5° while the three corrugated vessels failed at an average angle of 45.0° with a standard deviation of 5.0°. Although the sample size may be too small to document strength reliably, the differences are significant at the 0.05 level. Thus, the corrugated vessels again appear to be slightly stronger with respect to impact-induced stress. The slightly thicker walls of corrugated vessels may again be contributing to this difference.

In addition to subtle differences in strength, I also observed a striking difference in how plain and corrugated vessels broke during the pendulum impact tests. The plain pots all failed from cracks that extended from one side of the rim to the other through the base of the pot creating two, fairly symmetrical vessel halves. The corrugated vessels failed in more complex ways, but usually the cracks

Table II. Results of Impact Strength Tests on Plain and Corrugated Vessels Used for Different Amounts of Time

Vessel type	Hours of use	Falling-weight Test: No. of impacts	Falling-weight Test: Sum of drop heights (cm)	Falling-weight Test: Result	Pendulum impact test: No. of impacts	Pendulum impact test: Highest angle	Pendulum impact test: Result
Corrugated	608	18	873	Cracked			
Corrugated	608	3	123	Hole in base	7	40	Bottom cracked off
Plain	608	46	2875	Cracked			
Corrugated	301	64	4576	Cracked			
Corrugated	301	13	598	Hole in base	8	45	Bottom cracked off
Plain	301	16	760	Cracked			
Corrugated	8	55	3685	Cracked			
Corrugated	8	16	760	Hole in base	9	50	Cracked around vessel & to rim
Corrugated	8	8	348	Hole in base	7	40	Cracked around vessel & to rim
Corrugated	8	14	651	Hole in base	8	45	Bottom cracked off
Plain	8	7	301	Hole in base	6	35	Cracked from rim to rim
Plain	8	7	301	Hole in base	6	35	Cracked from rim to rim
Plain	8	17	816	Hole in base	7	40	Cracked from rim to rim
Plain	8	10	445	Hole in base	6	35	Cracked from rim to rim

extended around the circumference of the vessel following coil joins and resulting in a fairly intact base and upper body/neck segments. I have seen examples of both of these characteristic fracture patterns duplicated in ancient plain and corrugated pottery.

Figure 11 shows box plots of the MOR data from the biaxial flexure tests for all measured fragments from vessels with 8 h of cooking time. The data are grouped by vessel type (plain and corrugated) and vessel part (upper body and base). The corrugated sherds consistently failed at lower MOR values, and a Mann–Whitney U test confirms the statistical significance ($p < 0.001$) of the lower strength of corrugated vessel fragments indicating that differences are greater than expected from sampling error alone. Comparing average median MOR values for individual vessels also indicates that the corrugated vessels are slightly, yet significantly ($p < 0.001$), weaker than the plain vessels regardless of vessel part.

Discrepancies in results between the biaxial flexure tests and the impact tests probably derive from the former controlling for differences in wall thickness, and thus, eliminating it as a factor in strength comparisons. The greater similarity among corrugated and plain vessels in the median values of peak load at failure

Table III. Results of Biaxial Flexure Strength Tests on Fragments From Plain and Corrugated Vessels Used for Different Amounts of Time

		Upper body fragments				Base fragments			
Vessel type	Hours of use	Median peak Load (kg)	Mean MOR	Median MOR	*N* of fragments	Median peak load (kg)	Mean MOR	Median MOR	*N* of fragments
Corrugated	608	39.0	3.1	3.1	6	47.4	3.5	4.1	6
Corrugated	608	36.7	4.1	3.6	7	33.6	4.0	3.3	5
Plain	608	64.9	8.3	8.4	8	76.7	9.0	8.9	5
Corrugated	301	37.6	4.4	4.6	9	39.2	4.2	4.1	6
Corrugated	301	30.2	3.4	3.5	6	48.3	3.8	4.0	6
Plain	301	44.0	4.9	4.5	7	49.0	5.2	5.2	6
Corrugated	8	25.4	3.5	3.5	8	35.8	3.8	3.3	5
Corrugated	8	40.8	4.2	4.2	8	40.1	3.7	3.5	6
Corrugated	8	23.1	2.9	2.9	7	24.7	2.1	2.0	6
Corrugated	8	30.8	4.1	3.8	7	25.2	3.9	3.2	6
Plain	8	34.5	5.0	4.9	7	29.9	4.5	4.5	6
Plain	8	36.7	5.5	5.1	9	77.1	7.5	6.9	6
Plain	8	35.8	3.7	3.9	9	38.8	5.2	5.2	6
Plain	8	34.5	6.3	6.3	8	31.3	7.0	5.9	6

Note. MOR: Modulus of rupture.

(Table III), which does not control for wall thickness, supports this interpretation. If corrugated vessels are mechanically weaker than plain vessels given the same wall thickness as these results suggest, then it is probably the relatively poorer weld between coils and the uneven surface, both of which can concentrate stress, which accounts for the lower resistance of corrugated vessels to mechanical stress. However, because the two sets of tests also measure different aspects of strength (Neupert, 1994), it is also possible that corrugated vessels are more resistant to the stresses created by repeated impacts while plain vessels have greater resistance to the tensile stresses generated during bending. The small sample size and lack of control for wall thickness in the impact tests curtail our ability to explore this possibility further with existing experimental data.

Vessel Durability: Responses to Thermal Stress

Flaws and Failures From Use

I observed two kinds of physical alterations in the vessels that occurred as a consequence of use—pitting and cracking. No spalling such as that described by Schiffer *et al*. (1994) occurred during the cooking experiments. Pitting consists of the loss of small amounts of pottery from the interior surface of the base of a pot, and closely resembles pitting observed on the interior surface of ancient utility ware pottery from the Mesa Verde region (Pierce, 1999). The pieces removed are

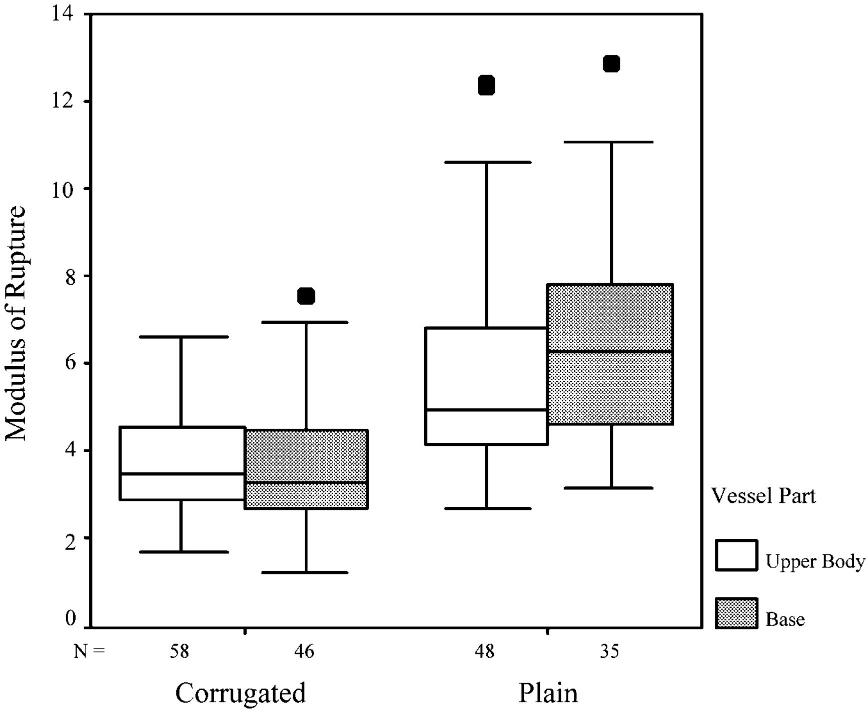

Fig. 11. Box plots of the strength (MOR) of upper body and base fragments cut from replica plain and corrugated vessels used for 8 h in cooking experiments.

not really spalls, but rather are flakes or slivers of the interior vessel surface. Using observations from the heating effectiveness and use-life runs, only seven of the 24 replica vessels developed interior basal pitting. For all but one of the pitted vessels, pitting occurred and reached its maximum extent within the first few hours of use. Of the seven vessels with pitting, all were used to cook mush, two were lined with pinyon pitch, and five have plain exteriors (Table IV).

None of the 24 vessels used in the heating effectiveness experiment developed cracks during the combined 8-h use in those experimental runs. However,

Table IV. Frequency of Replica Vessels with Pitted Interior Basal Surface After Use in Experiments by Factor Combination

	Plain surface		Corrugated surface	
Contents	Lined	Unlined	Lined	Unlined
Water	0	0	0	0
Corn mush	2	3	0	2

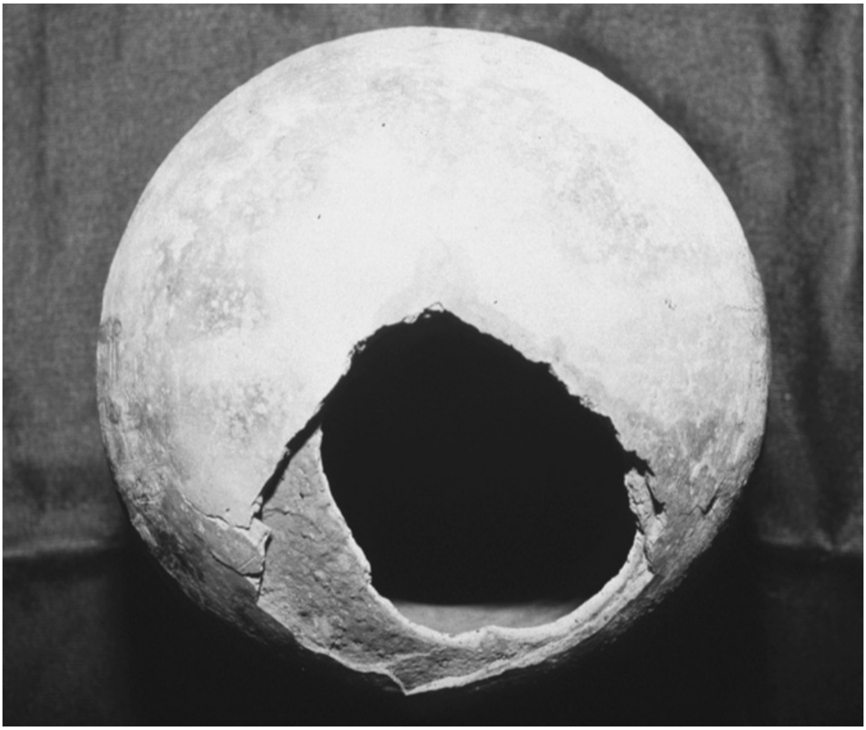

Fig. 12. Use-related vessel failure.

the extended exposure to thermal stress during the use-life experiment produced cracking in five of the eight vessels used in these extended tests. The vessels with cracking included all four plain and one corrugated, and cracking resulted in the complete failure of two of the plain vessels. No corrugated vessels failed during the use-life experiment.

In both cases of complete failure, light pressure on the inside surface produced a pie wedge-shaped hole in the base after cracks had caused significant weakening of the vessel wall (Fig. 12). In one of these vessels, the first cracks appeared on the surface after 47 h of use, and complete failure came after 287 h of use. In the second failed vessel, the first cracks became visible after 100 h of use, and failure occurred at the end of the last run of the experiment after 620 h of use. Among the three other vessels that developed visible cracks but did not fail completely, the first cracks appeared after almost 80 h of use in two of the vessels, including the only corrugated vessel to crack, while it took almost 215 h for cracks to appear in the third vessel. The remaining three corrugated vessels included in the use-life runs remained visually intact throughout the experiment.

In the four plain vessels, cracks appeared first on the exterior surface about 2.5–3 cm up from the very base of the vessel. These cracks initially spread in a narrow band horizontally around the circumference of the vessel as a network or web of short, interconnected, hairline fractures. Radial separation along some of the cracks in this horizontal band indicated clearly that the cracks extended into the vessel wall at a very shallow angle. In the two vessels that failed, cracks also extended down from this band of fractures toward the base. Eventually, these vertical cracks extended perpendicularly all the way through the wall. It was along these vertical cracks that failure ultimately occurred producing the pie wedge-shaped holes (Fig. 12). When the pots did fail, the network of shallow angle fractures resulted in numerous pieces missing some or all of one or both of the finished vessel surfaces (Fig. 13). These fragments closely resemble the alteration identified as spalling in utility ware assemblages (Pierce, 1999).

Cracks did eventually appear on the interior surface of some, but not all, of the plain vessels. These interior cracks always developed in the very base of the vessel, both as linear cracks across the base and circular cracks around the base, located well below the level of the band of horizontal cracks on the exterior surface. In the single corrugated vessel to develop cracks, interior surface cracks appeared first, followed almost 50 use-hours later by the appearance of horizontal

Fig. 13. Fragments produced from vessel failure.

cracks on the exterior surface at the same height above the base as occurred with the plain vessels.

Residual Strength

Thermal fatigue that does not lead to visible cracking or catastrophic failure of the vessel can still reduce use-life through weakening of the vessel wall thereby increasing its susceptibility to mechanical stresses. For the vessels that did not fail during the extended use-life experiments, I performed falling-weight, pendulum, and biaxial flexure strength tests to determine if any differences exist between plain and corrugated vessels in the amount of strength lost over different use intervals. The vessel sample for these strength tests includes two corrugated and one plain used for 600 h, and two corrugated and one plain used for 300 h. Not surprisingly, this extremely small sample produced ambiguous results. In the falling-weight impact test, two of the corrugated and both of the plain vessels cracked catastrophically while the other two corrugated vessels developed small holes in the base. The greater incidence of catastrophic cracking in the vessels subjected to extended use in comparison to those used for only 8 h indicates that some fatigue of the vessel walls had occurred through extended use (Table II).

Of the two corrugated vessels that cracked, the vessel used for 300 h required 63 drops of the ball bearing to fail while the vessel used for 600 h failed after only 18 drops. The single corrugated vessel used for 8 h that cracked during the falling-weight test of mechanical stress resistance required 55 drops to fail. Of the two corrugated vessels that developed holes, the vessel used for 300 h failed after 13 drops and the vessel used for 600 h failed after 3 drops. The three corrugated vessels used for 8 h discussed earlier also developed holes failed after an average of 13 drops. Thus, it appears that for corrugated vessels there is little or no strength reduction between eight and 300 h of use, but 70–75% of strength is lost between 300 and 600 h of use.

For the two plain vessels, the vessel used for 300 h required 16 drops to fail while the vessel used for 600 h failed after 46 drops. This unexpected result may derive from the differences in basal wall thickness between the two vessels (4.7 mm vs. 5.8 mm respectively), or possible slight differences in manufacture or firing. Unfortunately, no comparable data exist from plain vessels used for 8 h because all developed holes rather than cracking during the falling-weight test.

The only data available from the pendulum impact test is for the corrugated vessels that did not crack during the falling-weight test. The vessel used for 300 h failed when dropped from an angle of 45° and the vessel used for 600 h failed when dropped from 40°. The average drop angle for the vessels used for 8 h is 45°.

Biaxial flexure tests on pieces cut from the six vessels that survived the cooking phase of the use-life experiment are equally ambiguous (Table III). A box plot of MOR values for sherds cut from the base of the plain and corrugated vessels used for different lengths of time shows that the strength of corrugated vessels

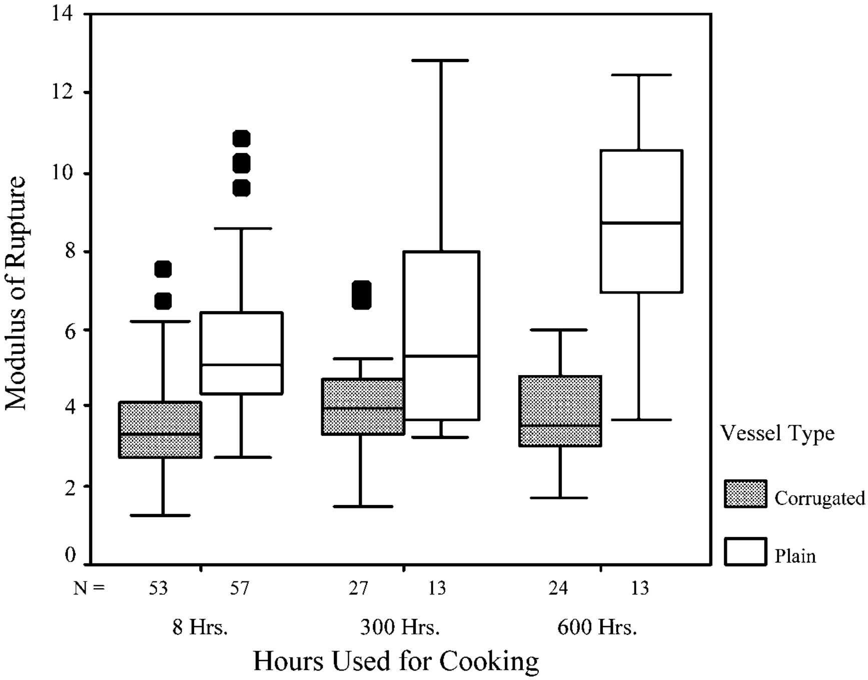

Fig. 14. Box plot of strength (MOR) of base fragments cut from replica plain and corrugated vessels used for different amounts of time in cooking experiments.

remained fairly constant while the strength of plain pottery appears to increase across the three use-life intervals (Fig. 14). To control for differences in original strength of the vessels, I computed a ratio of median MOR of the base sherds to the median MOR of the upper body sherds for each vessel. Figure 15 shows that these ratios generally vary little across different use intervals and most of the values are not significantly different from 1.0. This indicates that the strength of base pieces did not degrade significantly over use-life relative to upper body pieces. This result is difficult to explain and probably results from trying to use an extremely small sample to measure a complex phenomenon. However, it is possible that the development of cracks reduces stress and strain locally so that areas in between cracks retain their original strength while the overall strength of the vessel degrades.

Effective Use-Life

The development of subcritical fractures in the vessel wall of a cooking pot can degrade its heat transfer effectiveness by introducing voids that impede heat

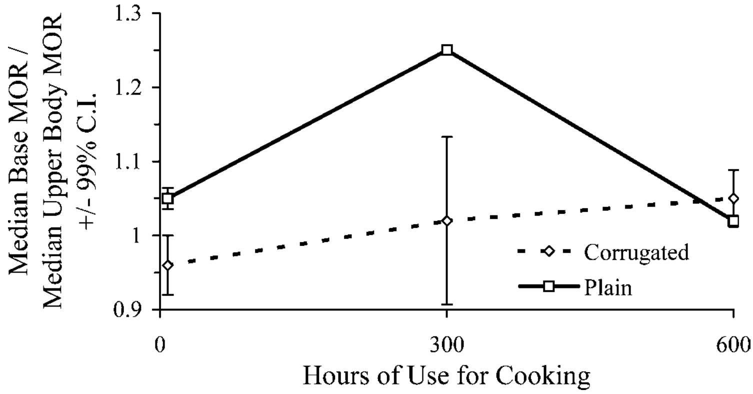

Fig. 15. Ratios of median base to median upper body strength (MOR) values for plain and corrugated replicas used for different amounts of time in cooking experiments.

flow. It is possible then, that through use, a vessel could become so ineffective that it is no longer practical for it to continue serving as a cooking pot although the vessel remains physically intact. Thus, the effective use-life of a cooking pot might be shorter than its use-life as determined by structural integrity.

Figure 16 shows the heating effectiveness (time to reach peak temperature) over the cumulative hours of cooking use to which the vessels were exposed. Although some variation exists among vessels and between runs of the same vessel, Lowess trend lines for both plain and corrugated vessels show that heating effectiveness remained fairly constant over the period for which these vessels were used. Because two of the plain pots failed during this experiment, it appears that the structural use-life of plain vessels is shorter than the effective use-life. Given that none of the corrugated vessels failed, it is still possible that corrugated vessels could remain structurally intact beyond the point at which they are no longer effective cooking pots. An experiment involving many more hours of use would have to be conducted to determine if this is the case.

Vessel Durability: Ease of Handling

Out of the nearly 2000 times I transported the plain and corrugated replicas used in the heating effectiveness and use-life experiments, I dropped only one vessel. This was a plain-surfaced vessel that slipped out of my hand when I was setting it down while teaching a class after the experiments were completed. Both the relatively small sizes of the replica vessels and the extreme care I exercised when transporting the vessels probably contributed to the low droppage rate. Larger vessels, which are more common in actual southwestern pottery assemblages, are

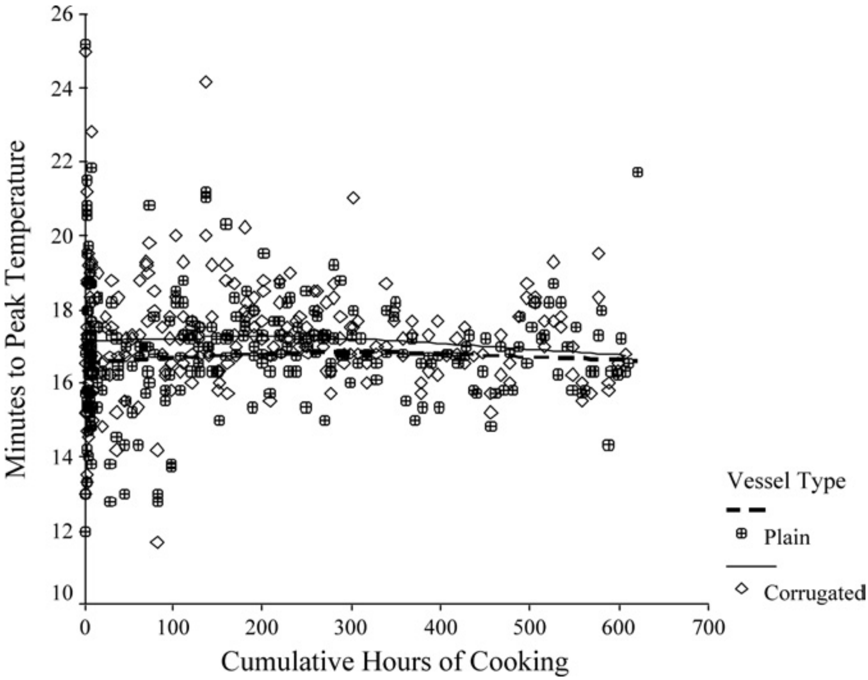

Fig. 16. Scatter plot of the heating effectiveness of plain and corrugated vessels over experimental use-life with Lowess best-fit lines for each vessel type.

heavier, and offer a broader surface for grasping which could have produced a higher droppage rate in the past. In addition, while handling the vessels after cooking, I frequently noted that the corrugated vessels were easier to handle hot than the plain vessels because less of the hot surface was in contact with my hands. If cooks handled their hot vessels with bare hands, this effect could also reduce the incidence of accidental pot drops.

DISCUSSION

Each of the three engineering properties investigated—manufacturing costs, cooking effectiveness, and use-life—show differences between plain and corrugated vessels that may have been important to their makers and users. In addition, observations made during the experiments indicate that plain and corrugated vessels may differ in their ease of handling during use. This discussion presents the likely causes and possible significance of these differences by drawing on engineering principles and evidence from the archaeological record.

For manufacturing costs, I found that the full-body corrugated vessels were considerably more time consuming, and thus more costly, to form than the early plain vessels. The large differences in forming times between the plain and corrugated vessels made for this study derive mainly from differences in coil size and application technique. If the same number of coils and degree of overlap were used to manufacture both plain and corrugated vessels, it is likely that forming times would be similar or that corrugated vessels could even take less time to form, as Blinman (1993) found, because the scraping step for the exterior surface would be eliminated. However, the use of a small number of wide, filleted coils in the plain versus the numerous smaller, overlapping coils in the corrugated should, and experimentally did, result in less time to form the plain vessels.

Given that vessels constructed with narrow, substantially overlapped coils are more time consuming to form than vessels made with large filleted, or nonoverlapped coils, as the size of coils decreased and the amount of overlapping application increased through time, the manufacture cost of Puebloan cooking pots likely also increased as well. Studies of sherd fracture patterns and exposed coil application in utility ware assemblages spanning the change from plain to corrugated pottery in southwestern Colorado indicate that coil size decreased and degree of overlapping increased during the tenth and eleventh centuries (Pierce, 1999, in press). This is the period during which neck-banding saw its greatest degree of elaboration and, later, full-body indented corrugation was adopted. If coil size and application technique are the main determinants of forming time variation, then forming costs would have increased during the tenth and eleventh centuries as potters adopted the use of small, overlapping coils to construct neck-banded and corrugated vessels.

I examined two aspects of cooking effectiveness—heat transfer and cooking control. Regarding the heat transfer properties of plain and corrugated vessels, these experiments demonstrate beyond any doubt that corrugation substantially degrades net heat transfer effectiveness unless vessel walls are made less permeable. This difference in heating effectiveness is a function of the greater exterior surface area of corrugated vessels. Although the extended surface area of a corrugated exterior does improve heat transfer rates, this is true for heat entering *and* leaving the vessel. When a vessel wall is permeable, liquid contents soak through the vessel wall and evaporate from the exterior surface. The heat energy used to change the liquid to a gas results in cooling of the vessel and its contents. The extended surface of corrugated vessels increases the rate of evaporative cooling producing a greater degradation of heating effectiveness than in plain surfaced vessels. The slightly elevated effectiveness of pitch-lined corrugated vessels over pitch-lined plain vessels in the first run when wall permeability was extremely low indicates that the greater exterior surface area of corrugated vessels does improve the transfer heat to the vessel contents. However, even slight increases in wall permeability eliminate this advantage because the area of the surface losing heat through evaporative cooling is considerably greater than the small portion of the vessel, the base, actually being heated during use.

However, when the permeability of the vessel wall is minimal, which fortunately occurs as a consequence of cooking food, evaporative cooling is limited, greatly reducing upper body heat loss. The fact that a single episode of cooking food greatly reduces the permeability of an unlined vessel wall suggests that users of plain and corrugated pottery in the past would probably have been unaware of their significant differences in heating effectiveness when unlined. Thus, under conditions of normal cooking use, the heating performance of corrugated vessels is only slightly less efficient than that of plain vessels. This reinforces studies discussed earlier that had undermined the dogma of improved heat transfer effectiveness of corrugated vessels because of the extended exterior surface.

The cooking experiments also demonstrate that the slightly degraded heat transfer performance of corrugated vessels has an additional benefit of improving cooking control through a considerable reduction in boilovers. The greater evaporative cooling of corrugated vessels may have allowed improved control of cooking by slight reductions in the rate and intensity of boiling. If simmering or other more controlled forms of moist cooking were preferred to boiling, corrugated vessels would have offered an important benefit. Because the exposed coils on the upper portion of the vessel body produce this effect, even partially corrugated vessels would have offered an advantage over scraped plain vessels in cooking control. Although boilovers can be avoided by other means such as using larger or more open vessels to cook the same amount of food, these adjustments introduce additional costs. Larger vessels involve greater manufacture costs whereas more open vessels lower heating effectiveness by allowing more heat loss from the opening of the vessel. How these costs compare to the higher cost of forming corrugated vessels has not been documented.

This improved cooking control would have appeared as exposed coils began to be used below the neck of vessels, and would have increased as more and more of the upper body surface was covered with corrugation. Regular use of corrugation below the neck occurred during the tenth and very early eleventh centuries in southwestern Colorado and elsewhere in the northern southwest (Pierce, in press, 1999).

Although most of my data on ease of handling are largely anecdotal, it does appear that a corrugated surface improves handling particularly when the vessels are hot. This improvement comes mainly from the increased surface roughness of corrugation, which both increases friction and reduces amount of hot vessel wall coming in direct contact with hands. Consequently, innovations that increased surface roughness, such as overlapping and indenting coils, would have improved the graspability of cooking pots particularly when these techniques were employed on the necks of vessels. Thus, the earliest forms of exposed coils, which were relatively wide and flat, would have offered little handling advantage over a plain surface. The introduction of overlapped coils in the late ninth century, which produced a clapboard-like surface, would have added considerably to surface roughness and perhaps improved handling. The addition of indentations to the overlapped coils during the tenth century also would have increased surface roughness and greatly reduced the amount of vessel surface coming into contact with hands grasping the vessels.

The use-life experiments generated two kinds of alterations or flaws—pitting and cracking. It seems likely that the pitting is produced by tensional stresses on the interior surface that cause a network of short, very shallow cracks to develop. These cracks create enough surface weakness to allow attrition of the surface to occur. The restriction of pitting to the lower portions of the vessel where tensional stresses would be greatest supports this interpretation. The association between cooking mush and pitting also suggests that there may be a chemical component to pitting, or that reduced vessel wall permeability encourages pitting. Finally, although the sample size is extremely small, the preponderance of pitted vessels with plain exteriors (71% of vessels showing pitting) suggests that plain vessels are more susceptible to pitting. If interior tensional stresses are the main cause of basal pitting and more stress develops within the wall of plain vessels than those with corrugation, this would explain why more pitting occurred on the plain cooking pots.

The rate and extent of visible crack propagation varied considerably among vessels. Given the extremely small sample size, it would be imprudent to generalize about these particular aspects of cracking at this time. However, an explanation of the consistent spatial pattern of crack development is warranted.

As discussed earlier, two thermal gradients exist within the vessel wall during cooking, and these gradients generate most of the thermal stress. One gradient extends through the wall between the heated exterior and the cooler interior, and the other extends up the vessel wall from the heated base to the cooler upper body. Figure 17 shows the average temperatures of the exterior and interior surfaces along a vertical profile of a replica vessel during use. Interior surface temperatures were not measured directly. Instead, the temperature of the liquid contents serves as a proxy measure of inside surface temperature. The difference between the interior and exterior surface temperatures at a given position on the vessel wall indicates the intensity of the thermal gradient through the wall, while exterior temperature differences vertically show the gradient up the wall.

Compressive exterior and tensile interior stresses would be greatest at the bottom of the pot where the thermal gradient through the vessel wall is the most extreme. Shear stress within the vessel wall would be most intense in the area of greatest change in exterior surface temperature. This is because the cooler interior surface acts as a constant constraining force on the vertical and horizontal expansion of the entire exterior of the vessel wall while, at the same time, the hotter basal portions of the exterior expand more than the cooler upper portions. Consequently, rapid change in exterior surface temperature creates a situation in which the hotter portions of the wall are being thrust into the cooler portions

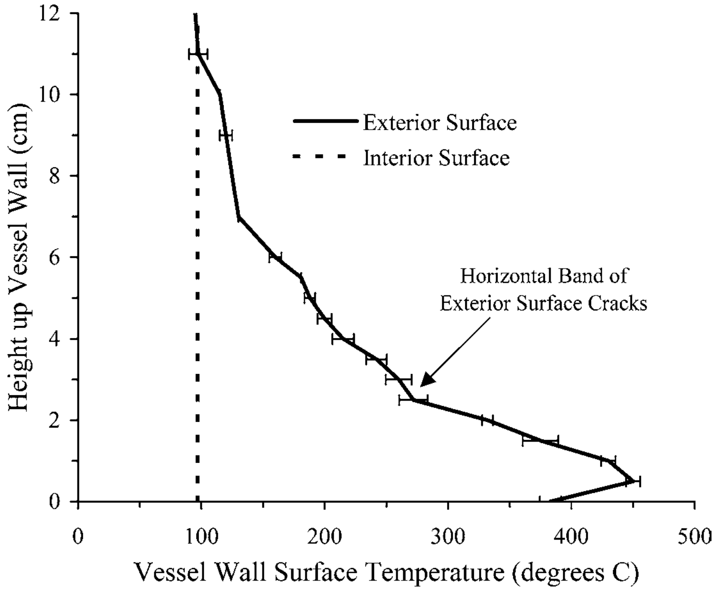

Fig. 17. Vertical profiles of exterior and interior vessel wall temperatures on replica vessels during cooking experiments. Error bars show the standard error of the mean temperature obtained from multiple measurements.

because of the differential expansion. Crack formation and propagation is one undesirable way of alleviating these thermal stresses within the vessel wall.

The low angle fractures produced by shear stress within the vessel wall appear on the exterior surface as a horizontal band of cracks at the upper edge of the zone of greatest vertical temperature change, and extend down through this zone of intense shear stress (Fig. 17). It is not surprising that these cracks would be the first to appear given the relative weakness of ceramics in the face of shear stress. Ultimately, combined shear and tensile stresses cause cracks to extend through the vessel wall leading to the failure of the vessel.

The lower incidence and slightly different pattern of development of flaws and failures in corrugated vessels indicate that these vessels respond differently to the potential thermal stresses generated during cooking. Corrugated pottery, as well as other pottery with a textured exterior surface, offers the potential to extend vessel use-life by altering the nature of stresses and, consequently, strains within the vessel wall. The most likely mechanism is the reduction of stress rather than increased stress resistance. An uneven, undulating exterior surface such as that produced with corrugation, although possibly acting to concentrate stress, also allows expansion to occur in the exterior portion of the wall without generating as much stress as occurs in a plain-surfaced vessel.

This phenomenon of stress reduction is analogous to use floating construction in bridges. In the case of corrugated pottery, the undulating exterior surface and the relatively poor weld between adjacent overlapping coils, which appears to reduce mechanical strength, can also alleviate thermal stress by allowing expansion to occur between coils. Both of these mechanisms potentially serve to reduce the constraint on lateral (vertical and horizontal) expansion that results in the buildup of thermal stress in a cooking pot. In addition, the undulating surface of corrugated vessels may alter the distribution of stresses at the surface where compressive stresses are at their maximum (Singh *et al.*, 1996).

Thus there is both experimental and theoretical support for the notion that corrugation results in a vessel with greater durability when used for cooking, but only if the corrugation extend down to the base of the vessel. Neck-banding, or other means of texturing only the upper surface of a vessel would not improve the use-life of ceramic cooking pots. Unfortunately, I could not quantify the difference in probable use-life experimentally. However, data from southwestern Colorado indicate that the accumulation rates of utility ware pottery decreased substantially after the introduction of full-body corrugation in the eleventh century suggesting a significantly increased use-life for these cooking pots (Pierce, 1999).

CONCLUSIONS

The reverse engineering analyses indicate that the shift from plain to corrugated cooking pots increased certain manufacturing costs, but also brought with it potential performance improvements. These improvements accrued with each step in the development of corrugated pottery. Neck banding may have made cooking pots easier to handle particularly when hot. Extending corrugation down below the neck to the upper body portion of the vessel improved control over cooking by limiting boilovers. Finally, using corrugation on the base of vessels would have reduced the thermal stresses associated with use in cooking, and thus increased their durability and functional use-life. Although these results pertain directly to Southwestern corrugated pottery, the nature of the performance benefits indicates that they would be manifest with any form of significant exterior surface texturing. However, identifying these performance benefits does not constitute an explanation of the observed technological changes. The fact that functional performance differences exist between plain and corrugated cooking pots does not answer the questions of how, or even whether, these differences can account for the complex history of changes documented in the archaeological record.

If these performance benefits do account for the development and adoption of corrugated cooking pots, we should be able to produce testable hypotheses that clearly place these performance properties in a causal framework incorporating details of Southwestern prehistory (Pierce, 1999). The fact that potential benefits appear with each step in the development of corrugation suggests that formulating hypotheses emphasizing functional vessel performance would be a worthwhile place to start. For example, if cooking practices changed to include an emphasis on extended boiling, such a change in the use of cooking pots would have placed greater pressure on cooking pot design with respect to cooking effectiveness and vessel durability. We would also expect to see a relaxing of these pressures on vessel design later as Pueblo potters returned to making plain cooking pots, and perhaps shifting pressure back to expedient manufacture. In addition we would expect to see technological or cultural impediments to the diffusion of corrugation to adjacent regions where similar pressures on cooking pot effectiveness and durability were present, but corrugation did not flourish. The use of paddle and anvil construction rather than coil building among the Hohokam (Haury, 1976), and the use of outside-in overlap of applied coils among the Pueblos of the Rio Grande Valley (Blinman and Price, 1998) and the possibly the Fremont (Geib, 1996) are examples of technological impediments to the diffusion of corrugation in adjacent regions.

Of course, it is also possible that the functional performance benefits documented in this study played no role in the development and adoption of corrugated cooking pots. Consequently, we should not restrict our hypotheses to those that give a causal role to the performance benefits of various forms of corrugation (see Feathers, 1990, 2003 for a similar treatment of the rise of shell tempered pottery in the eastern United States). Surface texturing in the form of neck banding and corrugation could serve a purpose completely unrelated to their performance in cooking. For example, given that the exterior surface of cooking pots often becomes covered with soot, texturing could be a form of decoration that would remain visible despite the buildup of soot. Such decorations could communicate information such as group affiliation, or even represent a form of costly signaling (Bird and Smith, 2005; Neiman, 1997). Plain and corrugated technologies could also have been associated with different cultural groups, and the change from plain to corrugated cooking pots follow from the replacement of one group with another. The presence of a continuous sequence of development from entirely plain to fully corrugated vessels, as well as other cultural continuities, over much of the northern Southwest suggest that this latter possibility is highly unlikely in most areas. By considering these rudimentary hypotheses separately, I do not mean to imply that they are mutually exclusive. Accounting for changes in Southwestern cooking pot designs in all their rich detail may involve all of these mechanisms and others as well.

The important point here is that reverse engineering should be seen as an essential part of describing ancient technologies in a way that makes valid explanation possible. Without the reverse engineering of plain and corrugated cooking pots presented here, we could still be trying to explain why the ancient Pueblo people adopted a cooking pot design with superior heat transfer capabilities, a common assumption that has been finally refuted. Now we can begin the process of formulating new hypotheses that incorporate knowledge of the actual performance properties of the vessels involved. Although many of the functional performance properties documented in this study are applicable to examples of plain and textured cooking pots documented elsewhere in the world, hypotheses ultimately developed to account for changes in Southwestern cooking pots are not so readily transferable. Viable explanations must take into account the local contexts within which specific technological changes occurred.

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