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Taphonomic Effects of Fire on Ostrich and Emu Eggshell

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ABSTRACT

Dinosaur eggshell and evidence for wildfires are common in the fossil record. The effects of fire on ostrich and emu eggshell, modern analogs for dinosaur eggshell, were examined by burning fragments in flames of two different temperature ranges for a series of time intervals. Percent mass loss increased directly with both time and temperature. Different treatment conditions also displayed regular patterns of change in color and curvature. Exposure of eggshell to flame results in dramatic physical changes, knowledge of which could be useful to paleontologists studying dinosaur nesting ecology.

INTRODUCTION

Fire is defined as the combustion of organic material in the presence of oxygen with the release of ash, heat, carbon dioxide, and other gases. Wildfires sculpt landscapes and induce both short and long-term effects in the environment (Finkelstein, 2004). Abundant evidence for fire exists in the fossil record, most notably in the form of abundant charcoal deposits (Scott, 2000; Glasspool et al., 2004), some of which have been found in association with dinosaur bones (Wegweiser, 2006; Brown et al., 2012). Burned bones and teeth exhibit characteristic changes in color and microstructure (Shipman et al., 1984). These characteristics, along with the presence of charcoal, have been used to implicate fire in the taphonomic history of dinosaur bones (Wegweiser, 2006; Brown et al., 2012).

Dinosaur eggshell has been found in Cretaceous deposits across the world. Particularly abundant deposits are known from France, China, and Montana (Carpenter et al., 1994). Although the effects of fire on bones and teeth have been examined, little is known regarding how fire could have influenced the preservation of eggshell. Dark-colored eggshell from Egg Mountain in Montana's Two Medicine Formation generated a large ammonia peak when analyzed for amino acid content, a result that led geochemist P. Edgar Hare to suggest it had been burned (Janssen et al., 2011). Increasing amounts of charcoal deposits discovered in Cretaceous sediments suggest that wildfires may have played an important role in Cretaceous ecosystems (Brown et al., 2012). Identification of the effects of fire upon eggshell could expand our understanding of factors influencing dinosaur reproductive success.

Extant avian eggshell has been used as a modern analog for dinosaur eggshell in taphonomic studies. Both extinct dinosaur and extant bird eggshell consist of calcium carbonate deposited in a protein matrix (Romanoff and Romanoff, 1949; Carpenter et al., 1994). Dinosaurs are taxonomically linked to birds, and the two groups share(d) some anatomical features, such as feathers (Janssen et al., 2011). They also share(d) similar reproductive strategies, including laying eggs in ground nests, brooding, and providing some parental care following hatching (Carpenter, 1999).

One of the early studies in eggshell taphonomy came about when ash from Mount St. Helens' 1980 eruption buried the nests of two species of gulls breeding on a colony in eastern Washington. Follow-up studies showed that the species, nesting habitat, and timing of the ashfall all influenced the preservation potential of particular nests (Hayward et al., 1989). Microscopic analysis of eggshell that had been buried by the ash revealed physical dissolution of the microstructure, which was attributed to the acidic conditions produced by the ash (Hayward et al., 1991). Additional experimental treatments of gull eggshell indicated that increases in temperature and acidity promote the rapid dissolution of the eggshell microstucture (Clayburn et al., 2004).

Most recently, Janssen et al. (2011) investigated the effects of high temperatures on gull and ostrich eggshell. Using a laboratory oven, they heated eggshell fragments at temperatures ranging from 200–800°C for different time intervals. The high temperatures converted the calcium carbonate to calcium oxide with the release of carbon dioxide. The eggshell fragments exhibited dramatic color changes, reverse curling, and decreases in mass in response to the treatments. Although there was some variation in color between the gull and ostrich eggshell, both types became darker at the lower temperatures and then paler at the higher temperatures. These results paralleled those observed for bones and conodont elements heated to high temperatures (Epstein et al., 1977; Shipman et al., 1984). The greatest decrease in mass occurred between 600–800°C, with ostrich eggshell fragments exhibiting a larger decrease in mass than the gull eggshell fragments.

Janssen et al. (2011) demonstrated that high temperature exposure can produce dramatic physical changes in avian eggshell. A likely medium for such temperatures in the natural world would be wildfires, which can range in temperature from 100–1400°C (Finkelstein, 2004). I examined the physical effects of a direct flame on ostrich (*Struthio camelus*) and emu (*Dromaius novaehollandiae*) eggshell, two robust types of extant avian eggshell that serve as useful analogs to dinosaur eggshell. I tested the hypotheses that 1) eggshell mass decreases in response to higher flame temperature and longer burn duration, and 2) treatment by flame may alter the color and curvature of eggshell.

MATERIALS AND METHODS

A total of six hatched ostrich (*Struthio camelus*) and six hatched emu (*Dromaius novaehollandiae*) eggshells were obtained from two different farms. Two of the ostrich eggshells came from Wild Dream Ostrich Ranch in Baroda, Michigan; remaining eggshells were purchased from Uniquely Emu Products, Inc. Fourteen fragments measuring ~1 cm^2 were collected from each eggshell. For each ostrich eggshell, two fragments served as controls and the other 12 were used in the trials. For each emu eggshell, four fragments served as controls and 10 were used in burn trials. Fragments were burned in flames within two different temperature ranges. A Bunsen burner was used to produce a flame between 400–600°C, and a Meker burner generated a flame between 950–1050°C. Treatment durations for the ostrich eggshell fragments in flames of both temperatures and the emu eggshell fragments in the lower-temperature flame were 1, 7.5, 15, 30, 45, and 60 min. For the higher-temperature flame, emu eggshells were burned for 1, 2.5, 5, and 7.5 min.

Prior to each trial, the eggshell fragments were weighed and then stored in a desiccator for a minimum of 24 h. Each fragment was then weighed again before being burned. Following each burn, the fragment was returned to the desiccator for another minimum of 24 h, and then weighed for a final time. All masses were determined to the 0.0001 g using a Mettler Toledo AG204 balance. Control fragments were treated in the same manner as the burned fragments except that they were not exposed to a flame: they were stored in the desiccator for the same amount of time as the experimental fragments and weighed when the experimental fragments were weighed.

For each burn, the eggshell fragments were placed concave-up over a slit in a 4x4 piece of Chromel (Nickel-Chromium alloy) mesh, supported by a ring stand. The average temperature of the flame at the slit was measured over a 3-min period before and after each burn using an Omega thermocouple (Model HH806); the mean of these two averages provided a burn temperature for each fragment. Each fragment was used only one time.

Following each burn, the color and curvature of each eggshell fragment were noted, along with any notable events that took place during the burn. The inner and outer surfaces of all the fragments from one ostrich and one emu eggshell were photographed to serve as representative samples for each trial. Photographs were taken using a Nikon CoolPix995 digital camera attached to the camera tube of a Leica WildM28 dissecting microscope. Fragments of the other five eggshells from each species were set aside in vials for later chemical analysis.

The mean percent mass losses for each trial were compared using ANOVA. A two-way ANOVA with replication (temperature by time) was used to analyze the ostrich eggshell percent mass loss. The emu eggshell percent mass loss was analyzed separately with two one-way ANOVAs: one for each temperature range. In addition I conducted Bonferroni *post-hoc* tests for pairwise comparisons of means using ProStat (2009) software. All tests were carried out at the 0.05 significance level.

RESULTS

Effects of Burn Temperature and Time on Mass Loss

The ostrich eggshell fragments decreased in mass as a result of the burn treatments, with an increase in burn duration or flame temperature resulting in greater mass loss (Fig. 1). A two-way ANOVA revealed that differences in both temperature and time resulted in significant differences in the percent mass lost during the treatment; moreover, flame temperature and burn duration showed significant interaction (Table 1). A Bonferroni's *post-hoc* test demonstrated significance when comparing trials from different flame treatments and between the first two time intervals in the hotter flame, and between the third and last two time intervals in that flame (Table 2).

The emu eggshell fragments also decreased in mass as a result of the burn treatments, with an increase in burn duration or flame temperature resulting in greater mass loss (Fig. 2). Both of the one-way ANOVAs indicated that an increase in burn duration resulted in a significantly greater mass loss by the eggshell. The hotter flame produced a percent mass loss of over 40%, whereas the cooler flame resulted in less than a 5% mass loss. The Bonferroni's *post-hoc* test of the data from the lower-temperature burns showed that each of the increases in burn duration produced a significant mass loss compared to the results of the 1-min burn (Table 3). In addition, the difference between the mass lost in the 7.5-min burn and that lost during the 60-min burn was also significant. For the emu eggshells burned in the hotter flame, the *post-hoc* test indicated that all of the burn durations resulted in percent mass losses that were significantly different from one another, except for those treated for 5 min and 7.5 min (Table 4). When the effects of the two flame temperatures were evaluated, all pairwise comparisons were significant except for between 1 and 7.5 min in the cooler flame (Table 5).

When subjected to the cooler flame, the ostrich eggshell experienced a greater percent mass loss than the emu eggshell. As shown in Figure 3, the ostrich eggshell experienced an average loss of up to 15% of its mass, while the emu eggshell lost on average less than 5% of its mass. In fact, after a short increase in mass loss between 1 min and 7.5 min, the emu eggshell experienced little increase in mass loss even when burned for 60 min. In the hotter flame, both ostrich and emu eggshell fragments eventually lost over 40% of their mass (Fig. 3). This occurred within 7.5 min for the emu eggshell. The ostrich eggshell lost 36% of its mass within the first 7.5 min of the burn.

Effects of Flame Exposure on Eggshell Color

Flame-treated eggshell fragments from both bird species exhibited dramatic changes in color. In general, the eggshell fragments initially darkened in color when exposed to flame and then whitened as temperature and/or burn duration were increased. When burned in the cooler flame, the outer surface of both types of eggshell fragments exhibited various blends of tan and blue as intermediate colors, whereas the inner surface appeared a grayish beige color following the pyrolysis of any membrane that had been present (Figs. 4 and 5). However, these colors were never observed when the eggshell fragments were burned in the hotter flame. Even brief exposure of only 1 min caused the eggshell to assume shades of black or white. As the burn duration increased, the amount of white increased and the black receded.

Effects of Flame Temperature on Curvature and Structural Integrity

The two species of eggshell reacted differently to the different flame temperature ranges. In the cooler flame, portions of the inner layer of the ostrich eggshell fragments often exploded off with a flash of light. In some cases, the entire inner surface was gone following a 60-min burn in the cooler flame (Table 6). Interestingly, these explosions were not observed when the eggshells were burned in the hotter flame. However, 26 of the 30 ostrich eggshell fragments burned in the hotter flame for 7.5 min or longer exhibited reverse curvature following the burn.

The emu eggshell did not explode in the cooler flame. However, many of the emu eggshell fragments split into two separate layers almost immediately upon exposure to the hotter flame. The inner layer often then curled in either direction on top of the outer layer, which remained flat. This splitting made the emu eggshell fragments difficult to remove from the wire mesh; it was often necessary to remove one portion and then the other. Both types of eggshell became fragile and powdery as a result of exposure to the hotter flame.

DISCUSSION

Both ostrich and emu eggshell fragments decreased in mass in response to flame treatment. When exposed to high temperatures, the calcium carbonate structure decomposes to calcium oxide and releases carbon dioxide gas (Janssen et al., 2011). This chemical decomposition most likely accounts for the mass loss experienced by the eggshell fragments.

My results parallel those of Janssen et al. (2011) who heated ostrich and gull eggshell fragments in an oven. Using thermogravimetric analysis, they identified a sharp decrease in mass between 550–800°C, with an average mass loss of 43.9% by 800°C. This corresponds to my results in which eggshell fragments from both species lost an average of 40–45% of their mass in the hotter flame treatment. Janssen et al. (2011) found negligible to small decreases in mass when heating eggshells below 600°C and sharp decreases in mass when the eggshells were heated between 600–800°C. Pairwise comparisons of my data revealed a similar difference in mass loss due to flame treatment, with significant differences between percent mass loss usually occurring when comparing trials from the different flame treatments.

Janssen et al. (2011) also noted that treatment temperature above 200°C had a much greater impact on the eggshell color than treatment duration. My observations agree here as well. Even a brief, 1-min exposure to the 900–1050°C flame dramatically altered the eggshell's color. Based on its post-burn color alone, one could know to which flame temperature the eggshell had been exposed. In addition, flame temperature appeared to have a greater impact on the percent mass loss than burn duration, again with even a brief exposure to the hotter flame resulting in greater mass loss.

The observed color changes parallel those reported by Janssen et al. (2011), who found that the outer surface of the eggshell fragments initially darkened, displaying tans and blues, and then whitened. Shipman et al. (1984) burned sheep and goat bones and teeth, which are composed of hydroxyapatite. The fire caused the bones and teeth to change from a neutral white to various yellows to browns and reddish-browns and purples before once again turning white. Conodont elements, composed of carbonate apatite, also go through a predictable series of color changes when exposed to high temperatures (Epstein et al., 1977; Rejebian et al., 1987). Heating conodonts resulted in irreversible changes in color—from pale yellow to brown to black to gray to opaque white to clear—that were both time and temperature dependent. A color alteration index (CAI) was developed and used to score conodont elements found in the field. The degree of color alteration correlated directly to the depth and duration of the conodont's burial. Yet another study has used the color differences in agglutinated foraminifera near hydrothermal vents to approximate the degree of thermal maturation of their enclosing sedimentary rocks (Gunson et al., 2000).

In all of these studies, color alteration has been shown to be a useful indicator of organic metamorphism. Similarly, understanding the color changes that occur in eggshell as a result burning provides another piece to the puzzle of eggshell taphonomy. However, this information must be interpreted in connection with other lines of evidence, as multiple factors including minerals in the soil could also influence the eggshell color (Shipman et al., 1984).

Dinosaur eggshell is classified using parataxonomy, which relies on physical characters of the eggshell and names it independent of attempts at determining what species laid it (Carpenter, 1999). These characters include macroscopic and microscopic features such as eggshell size, surface ornamentation, shell thickness, mammillae thickness, and pore pattern. Many of the ostrich eggshell fragments appeared dramatically different morphologically following burning due to the loss of the inner layer. Emu eggshells also separated into two layers as a result of some of the burns. If such eggshells were to be buried, it would be easy for the two layers to be separated from each other. Changes such as these should be considered by paleontologists attempting to classify eggshell that is suspected of being burned. Furthermore, the possibility of reverse curling should also be kept in mind. If observed in fossil eggshell, reverse curvature could indicate previous exposure to high temperatures.

In conclusion, fire produces dramatic changes in avian eggshell mass, color, and morphology. Due to its similar composition, dinosaur eggshell would likely have been susceptible to fire in ways similar to extant avian eggshell. The abundance of charcoal deposits in Cretaceous layers containing dinosaur bones suggests the possibility that some dinosaur eggshell may too have been burned. Further study of the changes in microstructure and chemical composition of eggshell as a result of burning should prove helpful in identifying a taphonomic signature for fire in eggshell.

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TABLE 1—Results from a two-way ANOVA with replication of the ostrich percent mass loss.

Ostrich	***F*-value**	**d.f.**	***p*-value**
Temperature	305.388	1	3.24E-25
Burn Duration	21.07125	5	4.25E-12
Interaction	5.252574	5	0.000458

TABLE 2—Probability matrix from the Bonferroni *post-hoc* test of the ostrich mean percent mass loss.

Flame Burn Time	Low 1	Low 7.5	Low 15	High 1	Low 45	Low 30	Low 60	High 7.5	High 30	High 15	High 60
Low/7.5	0.248										
Low/15	0.076	0.527									
High/1	0.013	0.165	0.444								
Low/45	0.005	0.087	0.274	0.740							
Low/30	0.002	0.043	0.158	0.513	0.747						
Low/60	0.001	0.021	0.088	0.339	0.531	0.761					
High/7.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000				
High/30	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.146			
High/15	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.140	0.981		
High/60	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.039	0.522	0.537	
High/45	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.033	0.480	0.495	0.948

TABLE 3—Probability matrix from the Bonferroni *post-hoc* test for the emu eggshell exposed to the 400–600°C flame.

Burn Duration	1 min	7.5 min	15 min	30 min	45 min
7.5 min	0.004				
15 min	0.000	0.405			
30 min	0.000	0.309	0.850		
45 min	0.000	0.144	0.518	0.647	
60 min	0.000	0.033	0.173	0.238	0.464

TABLE 4—Probability matrix from the Bonferroni *post-hoc* test for the emu eggshell exposed to the 900–1050°C flame.

Burn Duration	**1 min**	**2.5 min**	**5 min**
2.5 min	0.000		
5 min	0.000	0.003	
7.5 min	0.000	0.000	0.245

TABLE 5—Probability matrix from the Bonferroni *post-hoc* test for a comparison of the effects of flame temperature on emu eggshell.

Burn Duration	**Low/1 min**	**Low/7.5 min**	**High/1 min**
Low/7.5 min	0.605		
High/1 min	0.000	0.000	
High/7.5 min	0.000	0.000	0.000

FIGURE LEGENDS

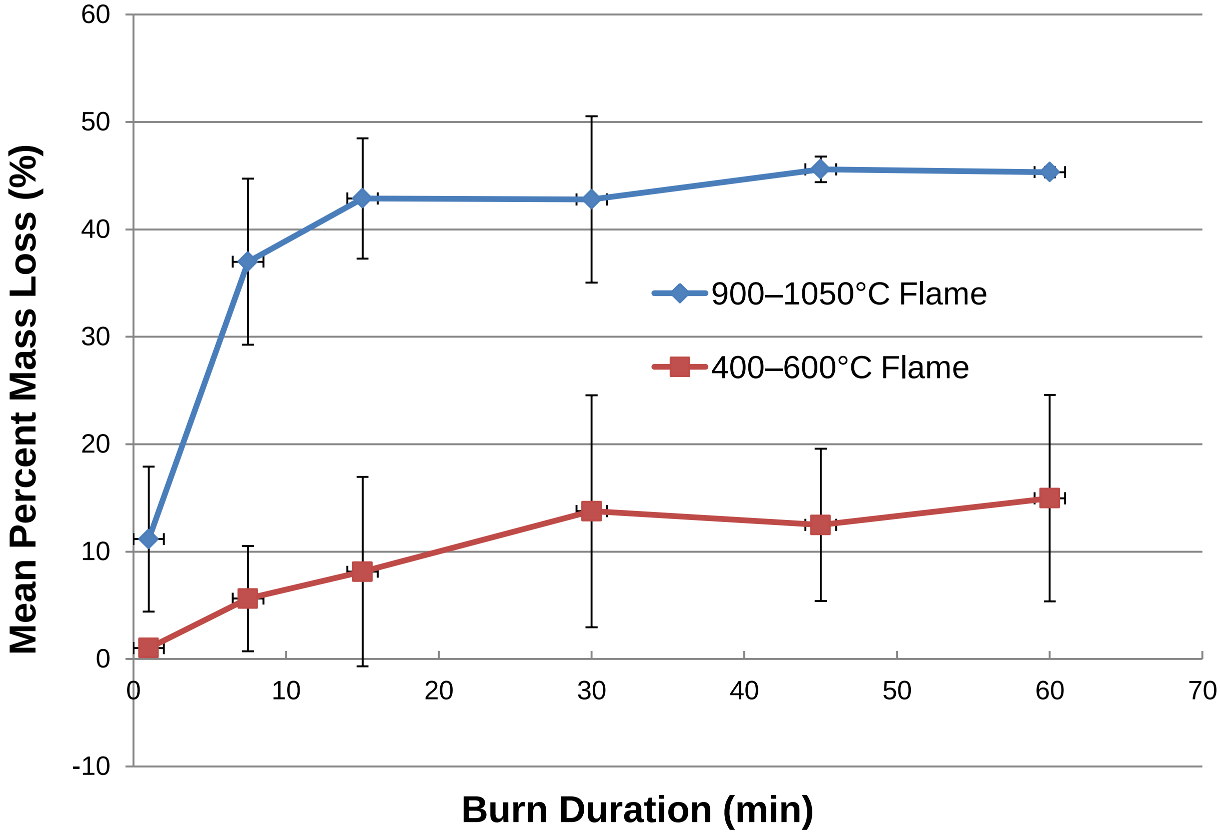
FIGURE 1—Mean percent mass loss of ostrich eggshell fragments. Each point represents the average percent mass loss of six eggshell fragments all treated in the same way. The lines do not represent a continuous measurement of mass loss over time.

FIGURE 2—Mean percent mass loss for emu eggshell fragments and results from the two one-way ANOVAs. Each point represents the average percent mass loss of six eggshell fragments all treated in the same way. The lines do not represent a continuous measurement of mass loss over time.

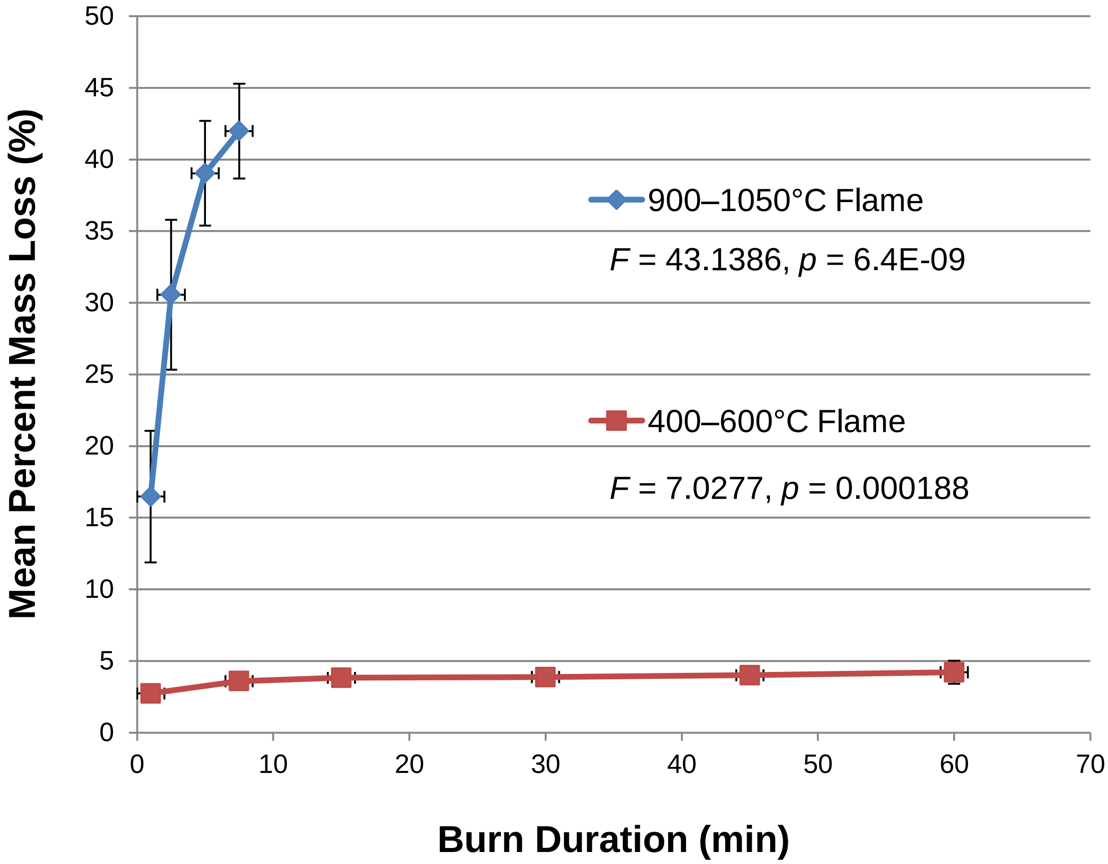
FIGURE 3—Graphical comparison of the mean percent mass loss of ostrich and emu eggshell fragments in flames of 400–600°C and 900–1050°C.

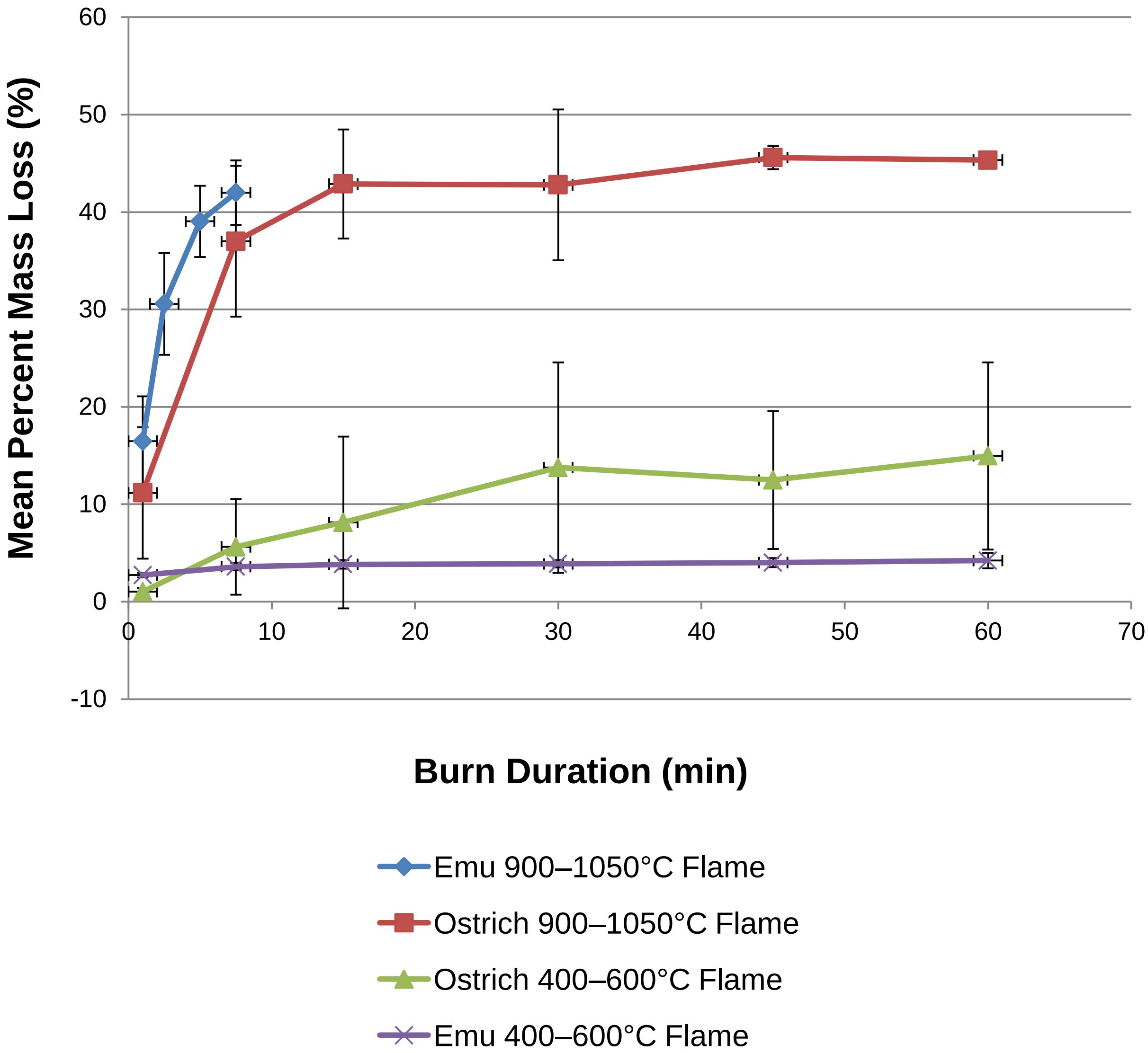
FIGURE 4—Photographs of control and burned ostrich eggshell fragments.

FIGURE 5—Photographs of control and burned emu eggshell fragments.

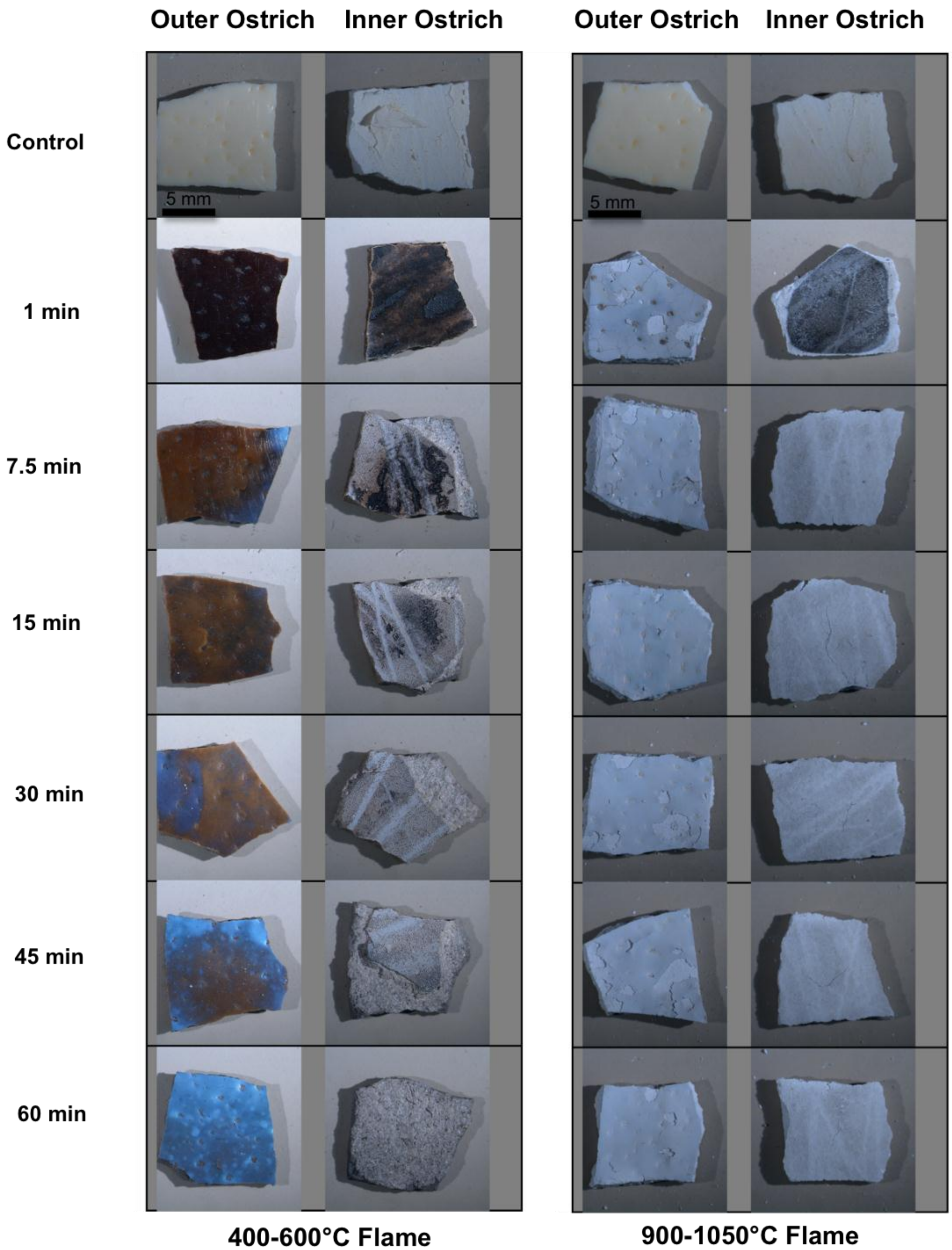


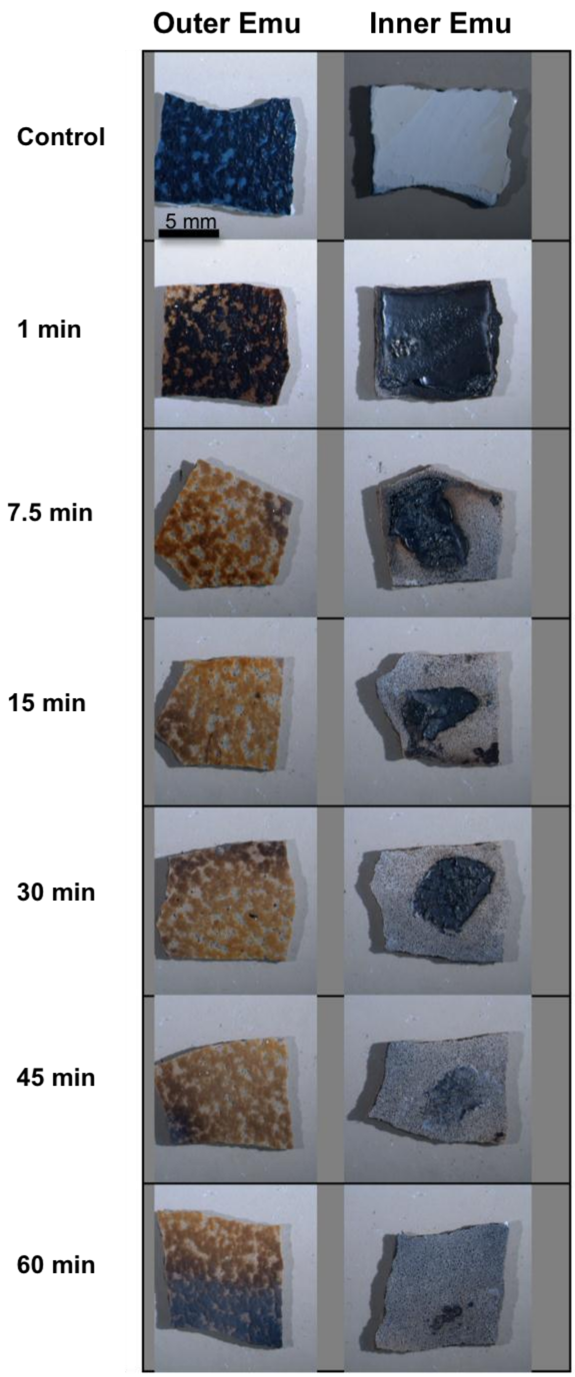
Mean Percent Mass Loss (%)
60
50
40
30
20
10
0
-10
0
10
20
30
40
50
60
70
900–1050°C Flame
400–600°C Flame
Burn Duration (min)


Mean Percent Mass Loss (%)
50
45
40
35
30
25
20
15
10
5
0
0
10
20
30
40
50
60
70
Burn Duration (min)
900–1050°C Flame
F = 43.1386, p = 6.4E-09
400–600°C Flame
F = 7.0277, p = 0.000188

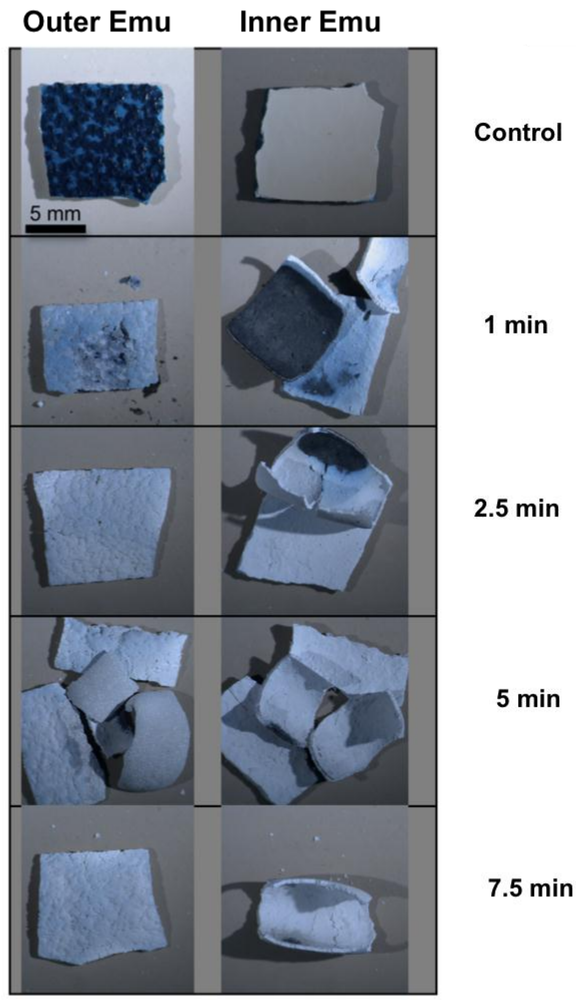


Mean Percent Mass Loss (%)
60
50
40
30
20
10
0
-10
0
10
20
30
40
50
60
70
Burn Duration (min)
Emu 900–1050°C Flame
Ostrich 900–1050°C Flame
Ostrich 400–600°C Flame
Emu 400–600°C Flame


Outer Ostrich
Inner Ostrich
Outer Ostrich
Inner Ostrich
Control
1 min
7.5 min
15 min
30 min
45 min
60 min
5 mm
5 mm
400-600°C Flame
900-1050°C Flame



400-600°C Flame



900-1050°C Flame

APPENDIX

Table A—Ostrich raw data**.**

Sample	Burn Duration (min)	Flame Temperature (°C)	Pre-burn mass (g)	Post-burn mass (g)	Mass Loss (g)	Percent Mass Loss (%)
A1	1	499.85	0.5029	0.4985	0.0044	0.874925
A2	7.5	467.15	0.4047	0.3812	0.0235	5.80677
A3	15	488.00	0.5019	0.4505	0.0514	10.24108
A4	30	493.70	0.492	0.3952	0.0968	19.6748
A5	45	481.45	0.5101	0.4203	0.0898	17.60439
A6	60	483.90	0.5082	0.4366	0.0716	14.08894
A7	1	965.25	0.446	0.405	0.041	9.192825
A8	7.5	974.65	0.563	0.4059	0.1571	27.90409
A9	15	990.70	0.5438	0.3722	0.1716	31.55572
A10	30	986.60	0.4398	0.3197	0.1201	27.30787
A11	45	983.10	0.4252	0.236	0.1892	44.49671
A12	60	982.80	0.4494	0.2475	0.2019	44.92657
B1	1	527.90	0.5185	0.5153	0.0032	0.617165
B2	7.5	495.95	0.4383	0.4276	0.0107	2.44125
B3	15	462.10	0.4611	0.4505	0.0106	2.298851
B4	30	564.60	0.4132	0.3423	0.0709	17.15876
B5	45	575.85	0.4098	0.3265	0.0833	20.32699
B6	60	568.45	0.3971	0.3128	0.0843	21.22891
B7	1	992.05	0.402	0.3701	0.0319	7.935323
B8	7.5	973.00	0.4225	0.2479	0.1746	41.32544
B9	15	994.10	0.4191	0.2335	0.1856	44.28537
B10	30	987.45	0.4083	0.226	0.1823	44.64854
B11	45	983.20	0.4219	0.2323	0.1896	44.93956
B12	60	1001.45	0.4028	0.2214	0.1814	45.03476
C1	1	516.10	0.3412	0.3356	0.0056	1.641266
C2	7.5	525.70	0.4385	0.4263	0.0122	2.782212
C3	15	507.95	0.3442	0.3332	0.011	3.195816
C4	30	503.90	0.3447	0.3333	0.0114	3.307224
C5	45	536.65	0.3411	0.3256	0.0155	4.544122
C6	60	543.65	0.3563	0.3449	0.0114	3.199551
C7	1	1025.80	0.3081	0.2327	0.0754	24.47257
C8	7.5	1020.45	0.3512	0.1908	0.1604	45.67198
C9	15	1007.95	0.3652	0.1953	0.1699	46.52245
C10	30	992.10	0.3056	0.1559	0.1497	48.9856
C11b	45	1006.15	0.3555	0.1851	0.1704	47.93249
C12	60	1004.90	0.4224	0.2271	0.1953	46.2358

D1	1	555.65	0.6623	0.654	0.0083	1.253209
D2	7.5	572.50	0.6593	0.5612	0.0981	14.87942
D3	15	571.05	0.5347	0.4	0.1347	25.1917
D4	30	563.65	0.5859	0.4076	0.1783	30.43181
D5b	45	468.95	0.586	0.502	0.084	14.33447
D6b	60	433.40	0.5567	0.4354	0.1213	21.78911
D7b	1	997.95	0.597	0.5568	0.0402	6.733668
D8b	7.5	980.60	0.6206	0.4238	0.1968	31.71125
D9	15	991.35	0.4895	0.2687	0.2208	45.10725
D10	30	998.90	0.5555	0.3045	0.251	45.18452
D11	45	1008.00	0.6078	0.3314	0.2764	45.47549
D12	60	987.50	0.6446	0.3526	0.292	45.29941
E1	1	496.10	0.4854	0.4807	0.0047	0.968274
E2	7.5	498.60	0.5024	0.4942	0.0082	1.632166
E3	15	470.45	0.5556	0.5319	0.0237	4.265659
E4	30	475.85	0.5035	0.4927	0.0108	2.144985
E5	45	486.10	0.5449	0.5285	0.0164	3.009727
E6	60	556.35	0.5583	0.5366	0.0217	3.886799
E7	1	1004.55	0.5917	0.5496	0.0421	7.115092
E8	7.5	1000.65	0.5083	0.3516	0.1567	30.82825
E9	15	1004.00	0.5639	0.309	0.2549	45.20305
E10	30	986.45	0.4926	0.2684	0.2242	45.5136
E11	45	972.05	0.4517	0.2463	0.2054	45.47266
E12b	60	1012.20	0.4539	0.2477	0.2062	45.42851
F1	1	527.60	0.454	0.4505	0.0035	0.770925
F2	7.5	514.80	0.4965	0.4657	0.0308	6.203424
F3	15	515.60	0.4798	0.4625	0.0173	3.605669
F4	30	505.85	0.5025	0.4529	0.0496	9.870647
F5	45	504.65	0.5115	0.4343	0.0772	15.09286
F6	60	527.40	0.5082	0.378	0.1302	25.61983
F7	1	1013.10	0.4537	0.4012	0.0525	11.57152
F8	7.5	1008.90	0.5626	0.3121	0.2505	44.52542
F9	15	1009.85	0.5729	0.3171	0.2558	44.65003
F10	30	998.95	0.5473	0.3003	0.247	45.13064
F11	45	998.90	0.4587	0.2511	0.2076	45.25834
F12	60	1009.10	0.4673	0.2566	0.2107	45.08881

Table B—Emu raw data.

Sample	Burn Duration (min)	Flame Temperature (°C)	Pre-burn mass (g)	Post-burn mass (g)	Mass Loss (g)	Percent Mass Loss (%)
G1	1	535.95	0.259	0.2512	0.0078	3.011583
G2	7.5	559.60	0.2432	0.2356	0.0076	3.125
G3	15	588.35	0.2836	0.274	0.0096	3.385049
G4b	30	455.40	0.252	0.2432	0.0088	3.492063
G5	45	529.40	0.3093	0.2986	0.0107	3.459425
G6	60	529.25	0.2327	0.224	0.0087	3.738719
G7c	1	981.40	0.2412	0.2139	0.0273	11.31841
G8c	7.5	996.60	0.2571	0.1654	0.0917	35.66706
G9	5	1027.20	0.2448	0.1445	0.1003	40.97222
G10b	2.5	987.35	0.2612	0.1989	0.0623	23.85145
H1	1	482.85	0.2162	0.2106	0.0056	2.590194
H2	7.5	483.20	0.2121	0.2038	0.0083	3.913248
H3	15	518.90	0.2011	0.1935	0.0076	3.779214
H4	30	539.55	0.2533	0.2433	0.01	3.947888
H5	45	525.40	0.2083	0.2006	0.0077	3.696591
H6	60	545.45	0.2191	0.2093	0.0098	4.472843
H7	1	991.65	0.2616	0.2296	0.032	12.23242
H8	7.5	980.90	0.24	0.141	0.099	41.25
H9b	5	984.25	0.2658	0.177	0.0888	33.40858
H10	2.5	996.60	0.2586	0.184	0.0746	28.84764
I1	1	491.25	0.301	0.2934	0.0076	2.524917
I2	7.5	502.05	0.2652	0.2565	0.0087	3.280543
I3	15	484.80	0.2957	0.285	0.0107	3.618532
I4b	30	538.95	0.2406	0.2311	0.0095	3.948462
I5	45	472.65	0.2501	0.2399	0.0102	4.078369
I6	60	487.75	0.2757	0.2668	0.0089	3.228147
I7	1	1011.70	0.2778	0.2351	0.0427	15.37077
I8	7.5	994.10	0.2739	0.1543	0.1196	43.66557
I9	5	981.95	0.333	0.1942	0.1388	41.68168
I10	2.5	1001.35	0.3029	0.2245	0.0784	25.88313
J1	1	454.25	0.251	0.2439	0.0071	2.828685
J2	7.5	447.75	0.2633	0.2537	0.0096	3.646031
J3	15	449.30	0.2361	0.227	0.0091	3.854299
J4	30	453.45	0.2454	0.2368	0.0086	3.504482
J5b	45	541.85	0.2725	0.2601	0.0124	4.550459
J6b	60	555.80	0.2399	0.2265	0.0134	5.585661
J7	1	988.70	0.2698	0.2263	0.0435	16.12305
J8	7.5	985.45	0.2327	0.1301	0.1026	44.0911

J9e	5	1005.60	0.2388	0.1543	0.0845	35.38526
J10	2.5	1027.10	0.2346	0.1581	0.0765	32.6087
K1	1	465.80	0.2398	0.2327	0.0071	2.960801
K2	7.5	450.75	0.2268	0.2176	0.0092	4.056437
K3	15	441.50	0.2458	0.2343	0.0115	4.6786
K4	30	481.40	0.2366	0.2259	0.0107	4.522401
K5	45	512.85	0.2388	0.2279	0.0109	4.564489
K6	60	523.35	0.2429	0.2324	0.0105	4.322767
K7	1	997.00	0.2776	0.2148	0.0628	22.62248
K8	7.5	1005.15	0.2499	0.1387	0.1112	44.4978
K9	5	994.10	0.2218	0.1301	0.0917	41.34355
K10	2.5	987.90	0.2407	0.1554	0.0853	35.4383
L1	1	515.80	0.256	0.2497	0.0063	2.460938
L2	7.5	533.95	0.2242	0.2163	0.0079	3.52364
L3	15	553.00	0.2198	0.2118	0.008	3.639672
L4	30	557.80	0.2617	0.2516	0.0101	3.859381
L5	45	557.90	0.2325	0.2239	0.0086	3.698925
L6	60	556.20	0.2514	0.2415	0.0099	3.937947
L7	1	995.15	0.2696	0.2125	0.0571	21.17953
L8	7.5	988.15	0.2366	0.1354	0.1012	42.77261
L9	5	1004.10	0.2762	0.1617	0.1145	41.45547
L10	2.5	1008.65	0.2553	0.1614	0.0939	36.78026

Table C—Ostrich ANOVA results.

ANOVA: Two-Factor With Replication

SUMMARY	Time1	Time 2	Time 3	Time 4	Time 5	Time 6	Total
Temp 1							
Count	6	6	6	6	6	6	36
Sum	6.125764	33.74524	48.79877	82.58823	74.91256	89.81315	335.9837
Average	1.020961	5.624207	8.133129	13.7647	12.48543	14.96886	9.332881
Variance	0.137678	24.03446	77.86185	116.7564	50.15296	92.25006	76.56343
Temp 2							
Count	6	6	6	6	6	6	36
Sum	67.02101	221.9664	257.3239	256.7708	273.5752	272.0138	1348.671
Average	11.17017	36.9944	42.88731	42.79513	45.59587	45.33564	37.46309
Variance	45.52307	59.8683	31.39435	60.03325	1.448459	0.227803	178.7867
Total							
Count	12	12	12	12	12	12	
Sum	73.14677	255.7117	306.1226	339.359	348.4878	361.827	
Average	6.095564	21.30931	25.51022	28.27992	29.04065	30.15225	
Variance	48.84754	306.5256	379.0764	310.2041	322.4465	293.5285	

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	14243.55	1	14243.55	305.3888	3.24E-25	4.001191
Columns	4913.891	5	982.7782	21.07125	4.25E-12	2.36827
Interaction	1224.919	5	244.9838	5.252574	0.000458	2.36827
Within	2798.443	60	46.64072			
Total	23180.81	71				

Table C—Emu ANOVA results for 400−600°C flame.

ANOVA: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Time 1	6	16.37712	2.72952	0.055259
Time 2	6	21.5449	3.590817	0.128316
Time 3	6	22.95537	3.825895	0.200423
Time 4	6	23.27468	3.879113	0.142781
Time 5	6	24.04826	4.008043	0.220466
Time 6	6	25.28608	4.214347	0.646857

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	8.164488	5	1.632898	7.027737	0.000188	2.533555
Within Groups	6.970512	30	0.23235			
Total	15.135	35				

Table D—Emus ANOVA results for 900−1050°C flame.

ANOVA: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Time 1	6	98.84665	16.47444	21.17144
Time 2	6	183.4095	30.56825	27.29922
Time 3	6	234.2468	39.04113	13.38457
Time 4	6	251.9441	41.99069	10.93019

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2354.897	3	784.9657	43.13863	6.4E-09	3.098391
Within Groups	363.9271	20	18.19635			
Total	2718.824	23				

Table E—Ostrich Bonferroni *post-hoc* test results.

Mean Difference Matrix

	Time 1	Time 2	Time 3	Time 7	Time 5	Time 4	Time 6	Time 8	Time 10	Time 9	Time 12
Time 2	4.603										
Time 3	7.112	2.509									
Time 7	10.149	5.546	3.037								
Time 5	11.464	6.861	4.352	1.315							
Time 4	12.744	8.14	5.632	2.595	1.279						
Time 6	13.948	9.345	6.836	3.799	2.483	1.204					
Time 8	35.973	31.37	28.861	25.824	24.509	23.23	22.026				
Time 10	41.774	37.171	34.662	31.625	30.31	29.03	27.826	5.801			
Time 9	41.866	37.263	34.754	31.717	30.402	29.123	27.918	5.893	0.092		
Time 12	44.315	39.711	37.203	34.165	32.85	31.571	30.367	8.341	2.541	2.448	
Time 11	44.575	39.972	37.463	34.426	33.11	31.831	30.627	8.601	2.801	2.709	0.26

Probability Matrix

	Time 1	Time 2	Time 3	Time 7	Time 5	Time 4	Time 6	Time 8	Time 10	Time 9	Time 12
Time 2	0.248										
Time 3	0.076	0.527									
Time 7	0.013	0.165	0.444								
Time 5	0.005	0.087	0.274	0.74							
Time 4	0.002	0.043	0.158	0.513	0.747						
Time 6	0.001	0.021	0.088	0.339	0.531	0.761					
Time 8	0.000	0.000	0.000	0.000	0.000	0.000	0.000				
Time 10	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.146			
Time 9	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.14	0.981		
Time 12	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.039	0.522	0.537	
Time 11	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.033	0.48	0.495	0.948

Rejection Matrix based on $p \leq 0.05$

	Time 1	Time 2	Time 3	Time 7	Time 5	Time 4	Time 6	Time 8	Time 10	Time 9	Time 12
Time 2	No										
Time 3	No	No									
Time 7	Yes	No	No								
Time 5	Yes	No	No	No							
Time 4	Yes	Yes	No	No	No						
Time 6	Yes	Yes	No	No	No	No					
Time 8	Yes	Yes	Yes	Yes	Yes	Yes	Yes				
Time 10	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No			
Time 9	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No		
Time 12	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	
Time 11	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No

Table F—Emu Bonferroni *post-hoc* test results.

Mean Difference Matrix (400–600°C Flame)

	Time 1	Time 2	Time 3	Time 4	Time 5
Time 2	0.861				
Time 3	1.096	0.235			
Time 4	1.15	0.288	0.053		
Time 5	1.279	0.417	0.182	0.129	
Time 6	1.485	0.624	0.388	0.335	0.206

Probability Matrix (400–600°C Flame)

	Time 1	Time 2	Time 3	Time 4	Time 5
Time 2	0.004				
Time 3	0.000	0.405			
Time 4	0.000	0.309	0.850		
Time 5	0.000	0.144	0.518	0.647	
Time 6	0.000	0.033	0.173	0.238	0.464

Rejection Matrix based on $p \leq 0.05$ (400–600°C Flame)

	Time 1	Time 2	Time 3	Time 4	Time 5
Time 2	Yes				
Time 3	Yes	No			
Time 4	Yes	No	No		
Time 5	Yes	No	No	No	
Time 6	Yes	Yes	No	No	No

Mean Difference Matrix (900–1050°C Flame)

	Time 1	Time 2	Time 3
Time 2	14.094		
Time 3	22.567	8.473	
Time 4	25.516	11.422	2.95

Probability Matrix (900–1050°C Flame)

	Time 1	Time 2	Time 3
Time 2	0.000		
Time 3	0.000	0.003	
Time 4	0.000	0.000	0.245

Rejection Matrix based on $p \leq 0.05$ (900–1050°C Flame)

	Time 1	Time 2	Time 3
Time 2	Yes		
Time 3	Yes	Yes	
Time 4	Yes	Yes	No

Mean Difference Matrix (Temperature Comparison)

	Time 1	Time 2	Time 7
Time 2	0.861		
Time 7	13.745	12.880	
Time 8	39.261	38.400	25.516

Probability Matrix (Temperature Comparison)

	Time 1	Time 2	Time 7
Time 2	0.605		
Time 7	0.000	0.000	
Time 8	0.000	0.000	0.000

Rejection Matrix based on $p \leq 0.05$ (Temperature Comparison)

	Time 1	Time 2	Time 7
Time 2	No		
Time 7	Yes	Yes	
Time 8	Yes	Yes	Yes