THE IMPACT OF WILDLAND AND PRESCRIBED FIRE ON ARCHAEOLOGICAL RESOURCES

by

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ABSTRACT

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Natural fire is a ubiquitous phenomenon that has affected the archaeological record at many different levels throughout prehistoric and contemporary times. Knowledge of this important site formation process is essential to understanding the differential forces that have, and continue to, shape the archaeological record. This work examines the potential for prescribed and wildland fire to adversely affect the interpretive integrity and preservation of archaeological materials.

The issue is addressed through field-based experimentation, laboratory experimentation, and field-based sampling of burned archaeological sites. Field-based experimentation performed in conjunction with prescribed burn programs was conducted in a variety of fuel types including mixed grass prairie, mixed grass prairie/ponderosa pine, mixed conifer, riparian, sagebrush, and piñon-juniper. The results of these investigations show that the important variables to consider when assessing the potential impact of prescribed fire on archaeological resources are: 1) fuel load; 2) fire behavior; 3) peak temperature and duration of heating; 4) proximity of artifacts to fuels; and 5) class of artifact.

Laboratory experimentation consisted of both trials in which selected archaeological material types were heated in a muffle furnace, and burned during wildland fire simulations conducted within a large combustion chamber/wind tunnel. The results of the furnace heating trials show that bone, shell, and certain varieties of chert are most prone to significant thermal alteration. The results of the laboratory wildland fire simulations illustrate the importance of fuel load, wind velocity, and flame angle as they relate to the significant

thermal alteration of various archaeological material types. Bone, shell, chert nodules, quartzite flakes, and bottle glass were shown to be most susceptible to thermal fracturing.

The field-based sampling project was conducted at Mesa Verde National Park where 72 Pueblo I-III habitation sites burned during wildland fire were sampled for observable fire effects. Vegetation type and fire severity were the most important variables affecting the thermal alteration of archaeological resources at the selected sites. The most pervasive form of thermal alteration observed was thermal spalling and fracturing of sandstone architectural elements. This was shown to have potential long-term negative implications for the preservation of sandstone architectural features at Mesa Verde.

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Any omissions, mistakes, and misinformation contained within this dissertation are the sole responsibility the author.

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CHAPTER 1

INTRODUCTION TO RESEARCH QUESTION

Introduction

The use of fire in human prehistory has undoubtedly had a profound influence on the evolutionary success of humans. Based on archaeological evidence, the earliest use of fire by hominids has been suggested to extent over one million years into prehistory, perhaps longer (Brain and Sillen 1988; see also Barbetti 1986; James 1989). Throughout prehistory, fire has served a variety of uses including, heating, cooking, heat treatment of chert, metallurgy, cremation, hunting, defense from predators, warfare, and land management. However, the signature of fire in the archaeological record may in some instances be confounded due to the occurrence of natural fires. Conner and Cannon (1991) have shown that burned logs from forest fire contexts can generate soil profiles that roughly approximate basin shaped hearths commonly recorded by archaeologists. Bellomo (1991; 1993; see also Bellomo and Harris 1990) has demonstrated that archaeologically derived hearths may be differentiated from more anomalous feature-like manifestations produced by natural fire via the documentation of basin-shaped configurations of oxidized sediment, and the use of magnetic and archaeomagnetic analyses.

Unfortunately, extensive laboratory analysis of sediments associated with hearth features is generally not within the research parameters of most archaeological investigations. Nonetheless, it is of primary importance that archaeologists are able to differentiate between transformations in the archaeological record generated by natural fire and those produced by human activity. The accurate analysis of the fire-related archaeological phenomena is not limited to the interpretation of hearth features alone. For example, does the occurrence of burned bone from an archaeological context necessarily suggest evidence of cooking; is burned human bone an indication of cremation, warfare, or cannibalism; does thermally altered chert suggest intentional heat treatment; do burned architectural features necessarily suggest intentional abandonment or warfare? Perhaps not, this is the impetus underlying the effort to understand the transformations affected on the archaeological record by natural fire.

Natural fire has far-reaching implications for the analysis and preservation of cultural materials deposited in the archaeological record. As such, investigating the impact of natural fire on archaeological materials has important implications for the interpretation of the archaeological record in general as well as the more specific preservation issues important to cultural resource management. The impact of wildland fire on the archaeological record is an important but often-overlooked site formation process. Schiffer (1987) makes little reference to the role of fire as a natural or cultural site formation process. Schiffer briefly addresses fire-related issues such as refuse burning, fire and site abandonment, charring as a wood preservative, and burned structures as a source of variability in the overall deterioration process of structures. Interestingly, wildland fire is entirely absent from his discussion of regional environmental site formation processes. Research conducted by Conner et al. (1989) and Conner and Cannon (1991) represent one of the few instances in which archaeologists have explicitly addressed the potential implications of natural fire as a site formation process.

Wildland fire is a ubiquitous phenomenon affecting landscapes on a global scale. Prior to 20th Century fire suppression activities in the Western United States, major wildland fires are estimated to have occurred every 5-10 years in grasslands (Collins 1990); 5-20 years in Sierra Nevadan forests (Skinner and Chang 1996); 10-30 years in ponderosa pine communities (Brown and Sieg 1996; Veblen et al. 2000); 20-150 years in the Northern Rocky Mountains (Arno 1980); 25-100 years in the Pacific Northwest (Agee 1990); 100 years in southwestern oak shrubland (Floyd et al. 2000); 300-400 years in southwestern piñon-juniper communities (Floyd et al. 2000); and 300-400 years in subalpine forests of the Yellowstone Plateau (Romme 1982). In addition to the common occurrence of wildland fire in North America, the use of landscape fire for a variety of cultural and ecological purposes has been documented among various Native American populations (Barrett and Arno 1982; Blackburn and Anderson 1993; Bonnicksen 2000; Boyd 1999; Brown 2000; Lewis 1973; Morris 1992; Pyne 1997; Turner 1991). Clearly, fire is an important site formation process affecting archaeological resources in the Western United States. Depending on the fire history of a particular area, historic and prehistoric archaeological sites may have been subjected to wildland fire multiple times over the course of their depositional histories. Moreover, given the recent occurrence of several large-scale catastrophic wildland fires within the Western United States and the prospect of augmented prescribed burning plans aimed at reducing hazardous fuel accumulations that generate these fires; the study of the impact of prescribed and wildland fire on archaeological resources has become particularly germane. The focus of the present dissertation project is to investigate the potential impact of wildland and prescribed fire on archaeological resources through laboratory experimentation, field-based experimentation, and post-fire sampling of archaeological sites that have been exposed to wildland fire conditions.

Project Purpose and Research Questions

The general purpose of the present dissertation project is to investigate the impact of wildland and prescribed fire on archaeological resources. This project was funded by the Canon National Parks Science Scholars Program, a cooperative program between the Canon

Corporation, National Park Service, and the American Association for the Advancement of Science. This program has an expressed interest in supporting research relevant to the interests of the National Park Service. The potential effects of prescribed burn programs and wildland fires on cultural resources within the parks-system have been an enduring concern for several years. As a result, a research design explicitly focused on addressing this topic was developed and implemented over the course of the project. The goals of the project are to identify the conditions under which selected artifact classes are significantly affected under prescribed and wildland fire conditions, and to assess the more long-term site formation process concerns related to burning of archaeological sites during wildland fires.

To address these issues, the overall project into three major research components:

1) Field-based Prescribed Burn Experiments

Field experiments were performed in conjunction with prescribed burn programs at several National Parks as well as Forest Service and Bureau of Land Management land. The experiments encompassed a variety of fuel types common to the Western United States. The purpose of the prescribed burn experiments was to establish soil surface heating time and temperatures profiles associated with a particular fuel type, and to document the range of observable thermal alteration affecting experimental artifacts that burned during the experiment. Details regarding this portion of the project are provided in Chapter 2.

2) Laboratory Muffle Furnace Heating Trials and Laboratory Wildland Fire Simulation

The laboratory muffle furnace heating trials were conducted in order to document the temperature ranges at which specific forms of thermal alteration affect common archaeological material types. During the experiment, artifacts representing a wide range of common material types, were heating during trials ranging from 100-1000°C. The experimental design and results of this experiment are presented in Chapter 3.

The wildland fire simulations were conducted at the USDA Intermountain Fire Sciences Laboratory, Missoula, MT. Under this phase of the project wildland fires of variable intensity were simulated in a combustion chamber housed within a wind tunnel at the laboratory. Here experimental artifacts were burned during the simulations and time/temperature and heat flux data were recorded on artifacts surfaces in order to correlate specific forms of thermal alteration with empirical heat energy data. In addition, two secondary experiments were also conducted. One focused on assessing the potential for natural fire to affect thermoluminescence signals in pottery, and the other focused on replicating the range of thermal alteration of Cliff House Formation Sandstone (Mesa Verde National Park) observed during in the field at Ancestral Pueblo sites burned during wildland fire. The details of this phase of the project are provided in Chapter 4.

3) Fire Effects Sampling of Burned sites at Mesa Verde National Park

During this phase of the project, a sampling strategy was developed to assess the immediate and long-term effect of wildland fire on Ancestral Pueblo sites at Mesa Verde National Park. Overall, 72 Pueblo I-III habitation sites that were burned during various major wildland fires (1934-2002) within the park were included in the sample. Specific information regarding this phase of the dissertation project is provided in Chapter 5.

Previous Research

The majority of published literature surrounding the effects of fire on archaeological resources originates from research that has been conducted in the form of post-facto observations of the aftermath of wildland fires (Conner et al. 1989; Conner and Cannon 1991; Eininger 1990; Johnson et al. 1991; Jones and Euler 1986; Lentz et al. 1996; Noxon and

Marcus 1983; Racine and Racine 1979; Romme et al. 1993; Switzer 1974; Traylor et al. 1990; Wettstaed 1992). In general, these studies consist of immediate post-fire inventories of affected archaeological sites that range in scope from general observation to comprehensive documentation of fire effects. Unfortunately, the majority of existing research has been limited to general post-fire observations that lack any systematic methodology to specifically document fire effects at the site or artifact level. Lentz et al. (1996) and Traylor et al. (1990) provide the most in-depth research on the subject of wildland fire and its impact on archaeological resources, and Conner et al. (1989) and Conner and Canon (1991) effectively place wildland fire within the conceptual framework of a regional site formation process. These studies are briefly summarized below.

The Traylor et al. (1990) investigation of the 1977 La Mesa Fire at Bandelier National Monument is an important contribution to the study of fire effects on archaeological resources due to the extensiveness of work conducted, which included post-fire inventory, excavation and sampling of four burned sites, as well as dendrochronlogy, ethnobotanical, palynological, soil, obsidian hydration, thermoluminescence, archaeomagnetic, and radiocarbon analyses of materials from sampled sites. In brief, the results of the study showed that the fire impact at selected sites was variable and largely dependent on fuel type, fuel load, and fire intensity. Significant thermal alteration of archaeological materials was generally limited to surface contexts at severely burned sites. Surface specimens from light to moderately burned sites were minimally affected, and materials from all subsurface contexts were unaffected regardless of fire severity.

The most prevalent fire effect observed by during the project was thermal spalling, cracking, and increased friability of tuff masonry elements associated with architectural features, particularly in severely burned areas. Ceramic materials from surface contexts exhibited combustive residue deposits, limited oxidation/color alteration of slips, possible thermal spalling of surface paint and slips, and possible increased friability of utilitarian sherds. Thermal alteration of lithic was limited to combustive residue deposits, no thermal fracturing was observed. Overall, significant thermal alteration of artifacts was not pervasive and was limited to surface specimens from severely burned sites. Ethnobotanical and palynological analyses conducted during the study indicated that subsurface heating generated by the fire was insufficient to affect pollen and plant remains from subsurface archeological contexts (Ford 1990; Scott 1990). Similarly, the fire did not affect archeomagnetic dates from selected subsurface hearth features, nor did it affect tree ring samples from selected sites within the study area (DuBois 1990; Robinson 1990). Results of the radiocarbon analysis were reported as inconclusive due to the lack of adequate control samples; however, theoretically contamination of modern charcoal with archaeological deposits has the potential to produce erroneous dates (Stehli 1990). Analysis of surface basalt and ceramic artifacts from surface context show that thermoluminescence dating may produce erroneously young dates; however, subsurface materials are unlikely to be affected (Rowlett and Johannessen 1990). Similarly, obsidian hydration analysis of obsidian artifacts from surface contexts showed a high prevalence of damaged hydration bands, whereas subsurface specimens were generally unaffected.

Lentz et al. (1996) conducted a similar investigation during a post-fire assessment of the 1991 Henry Fire that impacted several archaeological sites located in the Jemez Mountains of New Mexico. The researchers systematically sampled six Ancestral Pueblo archaeological sites using field sampling and laboratory methods. Field methods consisted of 1x1m test units excavated 20cm subsurface, 1x1m test units in areas where burned logs were present on structural components (if present), and 1x1m or 5x5m sample units to assess the degree of thermal spalling of tuff architectural elements. Laboratory analysis consisted of systematic thermal alteration attribute coding of artifacts collected from each of the selected sites. Overall, the methodology used to assess the fire impact on architectural elements and artifacts was more systematic and comprehensive than that implemented by Traylor et al. (1990); however, specialized analysis of ancillary archaeological information was limited to post-fire obsidian hydration analysis.

The results of the study showed that the degree of thermal alteration observed was variable at intra-site and inter-site levels and largely dependent on the fuel load and burn severity encompassing each site. In addition, subsurface materials were generally unaffected by the penetration of heat energy into the mineral soil, with the exception of a few instances where downed logs had burned for an extended period. These observations is consistent with that reported by Traylor et al. (1990), and further illustrate the important relationship between fuel load and fire severity as they condition the potential for significant thermal alteration of archaeological resources.

Significant thermal alteration of tuff architectural elements included thermal spalling, fracturing, and increased friability, the extent of which was directly related to fire severity. Artifact classes collected during sampling included ceramics (black-on-white, utility), lithic (chert, rhyolite quartzite and obsidian), and ground-stone. Post-fire analyses of these materials showed that combustive residue deposition was the most pervasive fire effect observed. Thermal spalling, oxidation, and pigment alteration of ceramics was observed at low frequencies, lithics exhibited low incidences of potlid fracturing and crazing, and thermal alteration of ground-stone specimens was generally limited to combustive residue deposition. Obsidian hydration analysis of 10 specimens showed that the fire did damage hydration rinds;

however, extent of damage could not be specifically determined due to the lack of pre-burn comparative samples (Origer 1996).

Regarding the thermal alteration of archaeological materials in general, the researchers illuminate the importance of making the distinction between “fire effect” and “damage.” Wildland fires will undoubtedly generate fire effects that impact archaeological resources; however, the extent to which materials sustain significant structural damage is variable. Combustive residue deposits, defined by Lentz et al. (1996:48) as “sooting” (“carbonized particles clinging to the surface of the item”) and “adhesions” (“sticky black substance of unknown origin”) can be referred to as a fire effect that does not necessarily damage archaeological resources. What the authors refer to, as “adhesions” consists of a highly nitrogenous condensate tar that forms on cooler surfaces (i.e., archaeological materials) below combusting organic fuels (Yokelson et al. 1997). “Sooting” is most likely the byproduct of the pyrolysis and combustion of organic fuels, referred to as “char” by DeBano et al. (1998:23), a substance that is neither an intact organic compound nor pure carbon. The combustive residue deposits should be considered a fire effect; however, they do not generally constitute damage of archaeological resources subjected to wildland or prescribed fire conditions. These deposits do weather from the surfaces of artifacts with time (see Chapter 4). Conversely, significant forms of thermal alteration such as thermal spalling, thermal fracturing, and heat-induced deterioration among various artifact classes does, with certainty, constitute permanent damage since the structural integrity of affected materials has been altered or destroyed indefinently. Clearly, wildland fire can impact archaeological resources to the extent that the interpretive value of the archaeological record has been significantly altered.

Other relevant work on the subject of wildland fire and archaeological resources includes research conducted by Conner et al. (1989) and Conner and Canon (1991) in the aftermath of the 1988 fires at Yellowstone and Grand Teton National Parks. The focus of these works was to illuminate the fact that wildland fire is an important regional-scale site formation process. Although the empirical data, which was based on generalized post-fire observations and testing of one archaeological site, is somewhat limited, the authors were able to derive some basic conclusions regarding wildland fire as a site formation process. The authors suggest that: 1) within burned areas wildland fire produces a mosaic burn pattern with sharply demarcated boundaries; 2) significant thermal alteration of bone and lithic artifacts at archaeological sites will be limited to the charred layer within the soil profile or within the first 10cm of the burn level (unless root systems have been combusted); and 3) wildfires can produce oxidized soil features and ash pockets that may roughly approximate cultural features. Within the fire effects literature, the authors are the only researchers that adequately document the broad implications of wildland fire as it relates to the conceptual framework of a regional site formation process.

Regarding the impact of prescribed burning on archaeological resources, several researchers have performed experiments in conjunction with prescribed fires to assess the immediate effect of burning on archaeological resources (Benson 2002; Brunswig et al. 1995; Deal and McLemore 2002; Green et al. 1997; Halford and Halford 2002; Hanson 2001; Kelly and Mayberry 1980; Sayler et al. 1989 (see also Picha et al. 1991); Smith 2002; Solomon 2002). However, the majority of this research has been performed with the purpose of assessing the impact of prescribed fire on obsidian, particularly as it affects obsidian hydration rinds. With the exception of Brunswig et al. 1995 and Sayler et al. 1989, few researchers have adequately assessed the impact of prescribed fire on a wide range of common archaeological materials, and none have done so within the contexts of variable fuel types. Brief summaries of each of the studies cited above are provided in Chapter 2. Overall, the combined body of literature on the subject offers important information on the impact of fire on archaeological resources; however, more extensive and systematic research needs to be conducted to fully develop a base from which to assess fire impact.

In addition to the limited archaeological literature that addresses the impact of wildland fire and prescribed fire on archaeological resources in general, some researchers have specifically assessed the potential for thermal alteration of obsidian and prehistoric ceramics with in the context of natural fire. Moreover, there exists additional ancillary information on the thermal alteration of specific material types can also be gleaned from additional sources. These include sources from the archaeological literature that pertain to the thermal alteration of chert, thermal alteration of bone, and ceramic studies. Brief summaries of research most relevant to studying the impact of wildland and prescribed fire are provided in the following sections.

Thermal Alteration of Chert

The majority of archaeological literature surrounding the thermal alteration of chert is concerned with the intentional heat treatment of lithic raw materials during prehistory. In attempting to replicate the production of prehistoric lithic artifacts, Crabtree and Butler (1964) found it useful to heat treat lithic material in order to enhance flaking qualities. It is now well accepted that prehistorically, chert was heat treated to enhance workability. Numerous researchers have conducted research concerned with the intentional heat treatment of various types of chert (Ahler 1983; Beauchamp and Purdy 1984; Bleed and Meier 1980; Collins and Fenwick 1974; Domanski and Webb 1992; Flenniken and Garrison 1975; Gregg and Grybush 1976; Griffiths et al. 1987; Hester 1973; Joyce 1985; Mandville 1973; Melcher and Zimmerman 1977; Olausson 1983; Ozker 1976; Patterson 1984, 1995; Perkins 1985; Price et al. 1982; Purdy 1974; Purdy and Brooks 1971; Rick 1978; Rick and Chappell 1983; Robins et al. 1978; Rondeau 1995; Roberts et al. 1978; Schindler et al. 1982; Shippee 1963; Weymouth and Mandeville 1975). Luedtke (1992) also provides an intensive summary of the physical characteristics of chert as well as an overview on the effects of thermal alteration of cherts. Although the studies on intentional heat treatment do not specifically address the impact of wildland fire or prescribed fire on lithics, they do provided a wealth of important information concerning the thermal alteration of lithic raw materials

Purdy (1974) conducted the most comprehensive study involving the thermal alteration of chert. When chert is heated to temperatures between 100-150˚C, free water is evaporated from pores and cracks (0.4-2.0% weight loss) (Purdy 1974). At temperatures between 350-500˚C the chemically bound water within the chert is driven off, and sulfur and iron compounds begin to oxidize (Purdy 1974; Griffiths et al. 1987; Shepard 1971). Schindler et al. (1982) have also observed that goethite oxidizes to hematite at temperatures between 200-300˚C. At temperatures above 500˚C, carbon and other non-silica materials begin to oxidize, decompose, dehydrate, and potentially fuse (Shepard 1971). The observable effects of thermal alteration of cherts include; color change, increased luster, reduced tensile strength, fracturing (blocky/angular), fracturing (potlid), and crazing (internal fracturing) (Ahler 1983; Griffiths et al. 1987; Schindler et al. 1982; Purdy 1974). Depending on the variety of chert, the color change associated with heating is the result of changes within its internal mineral structure. In the instance of thermal alteration of cherts from Florida, there is often a color shift from pink to red, which is the result of various iron compounds oxidizing to hematite (Purdy 1974). In Bald Eagle jaspers (Pennsylvania), a shift from yellow to red is the result of goethite being thermally altered to hematite (Schindler et al. 1982). In general, a color change within cherts and jaspers with heating is related to the alteration of iron minerals such as hematite, goethite, limonite, and pyrite (Luedtke 1992).

The lustrous quality in chert results from light being reflected from the surface of the material, and is largely dependent on mineralogy and surface characteristics (Luedtke 1992). Thermally altered cherts tend to exhibit an increased luster or gloss (on newly flaked surfaces after the material has been heat treated). Three explanations for increased luster with heating have been suggested; 1) Light is increasingly reflected off of fractured quartz grains (Purdy and Brooks 1971); 2) An increase in the number of fluid inclusions that reflect light occurs with heating (Griffiths et al. 1987); and 3) Altered hematite crystals increase light reflection (Schindler et al. 1982). These explanations are specific to the particular raw materials and experimental conditions used by each researcher; however, there is a general consensus that lustrous qualities are related to a change in microcrystalline structure and subsequent change in the refraction of light.

The reduction of tensile strength in lithic materials is often attributed to heat treatment. Indeed, the heat treatment of particular varieties of raw materials does enhance their workability (Bleed and Meier 1980; Crabtree and Bulter 1964; Rick 1978; Rick and Chappell 1983). The most widely excepted explanation for this occurrence is that it heat treatment allows a fracture to propagate across the microcrystalline quartz grains within the lithic material as opposed to around them (Purdy and Brooks 1971; Purdy 1974). In addition, heated cherts have a smoother fracture surface topography under SEM magnification as compared to unheated cherts (Luedtke 1992). Two explanations for this have been suggested; 1) Heating results in the fusion of silica leading to a denser structure; 2) Heating results in cracking which in turn increases fracturability (see Luedtke 1992:95-96). Regardless of a specific explanation, the heating of chert does affect its tensile strength and fracturability. Researchers have also shown that it is important to heat treat material slowly over a long period of time, and at temperatures below certain critical thresholds, which can range from between 250-450˚C depending on the variety of lithic material (Ahler 1983; Griffiths et al. 1987; Purdy 1974; Schindler et al. 1982). Researchers point out that if materials are heated too rapidly, or above their critical maximum temperature, thermal shock and fracturing will occur. These are precisely the parameters that characterize heating of surface materials during wildland and prescribed fire. That is, surface heating during wildland or prescribed fires is not uniform, with the potential for temperatures to rise and fall sharply depending on fire behavior and fuel type/loading.

Fracturing of materials subjected to heat is generally the result of thermal stress. Thermal stress occurs when a portion of the material becomes differentially warmer or colder than another resulting in an uneven rate of contraction or expansion resulting in heat-induced fracturing (Luedtke 1992). Quartz has a high coefficient of thermal expansion, experiencing a 3.76% expansion in volume when heated to 570˚C (Winkler 1973). Since chert is composed primarily of microcrystalline quartz, it is susceptible to thermal stress (Luedtke 1992). Heat induced fracturing in lithics can take the form of large blocky/angular fragments, potlid fracturing, or surface crazing.

Blocky and angular fracturing is often the result of rapid heating in which the original piece of raw material explodes into multiple fragments (Purdy 1974). The release of pressure within lithics is related to presence of water within the material's internal structure. Water is turned to gas at 100˚C; however, under pressure water will remain in liquid form until its critical temperature (365˚C, the temperature at which gas cannot be liquefied) is reached (Luedtke 1992; Weymouth and Williamson 1951). If water is present deep within the material when it is heated, it may be transformed to steam as it approaches the critical temperature for water. Steam can produce internal pressure within the material that is capable of generating an explosion and subsequent shattering of the material (Luedtke 1992). Potlid fracturing is attributed to the rapid heating and cooling of raw materials (Ahler 1983). Potlid fractures result from differential heating and pressure release probably due to steam buildup in areas of the material that has impurities or high moisture content. The fracture is characterized by a circular pit on the surface of the specimen. Crazing is the result of internal fracturing and takes the form of very fine non-linear cracks, similar to a spider web pattern, on the surface of a specimen (Ahler 1983). Crazing also occurs as the result of differential heating and pressure release. These forms of thermal fracturing have been observed in the field during post-fire inventories and prescribed fire experiments (Benson 2002; Lentz 1996; Lentz et al. 1996; Rondeau 1995; Sayler et al. 1989).

Thermal Alteration of Obsidian

As a volcanic glass, obsidian has excellent flaking qualities requisite for tool manufacture, and as such, was commonly utilized during prehistory. Archaeologists commonly use obsidian hydration analysis to effectively date obsidian artifacts via quantification of moisture uptake measured in hydration rinds that has occurred since artifacts were flaked (see Anovitz et al. 1999; Friedman and Long 1976; Friedman and Smith 1960; Friedman and Trembour 1983). In addition, geochemical trace element analysis of obsidian artifacts is often used to source the locations from which the raw material was initially quarried (Glascock et al. 1999; Hatch et al. 1990; Hughes 1988; 1994). While it remains relatively clear that thermal alteration of obsidian does not affect its geochemical composition (Shackley and Dilian 2002); it is quite clear that exposure to heat does negatively affect hydration rinds. The findings of several researchers suggest that obsidian hydration bands begin to be altered by heating at approximately 250°C, become significantly affected at approximately 400°C, and may be completely destroyed at temperatures exceeding 700°C (Benson 2002; Deal and McLemore 2002; Green et al. 1997; Findlow and Garrison 1982; Halford and Halford 2002; Mazer et al. 1991; Origer 1996; Ridings 1991; Smith 2002; Solomon 2002; Steffen 2002; Trembour 1990). As such, diffuse or destroyed hydration rinds render a specimen unsuitable for obsidian hydration analysis. Thermal alteration of obsidian and subsequent hydration rind damage is likely to occur where obsidian artifacts are directly exposed to prescribed and wildland fire conditions.

In addition, some researchers have documented heat-induced morphological change of obsidian during laboratory heating experimentation (Bennett and Kunzmann 1985; Nakazawa 2002; Steffen 2002; Trembour 1990). Most researchers are in general agreement regarding types of morphological change associated with the thermal alteration of obsidian. Steffen (2002:163) provides the most comprehensive description of various forms of thermal alteration observed for obsidian. These definitions are summarized as follows:

Matte Finish: Surface dulling similar to weathered or lusterless patina.

Surface Sheen: metallic-like surface luster, cause uncertain, but may be due to organic carbon buildup and/or bubble formation and shallow microscopic crazing.

Fine Crazing: Network of shallow cracks forming closed polygons on fresh fractures and flaked surfaces, likely due to differential thermal expansion/contraction.

Deep Surface Cracking: Shallow crevices formed on artifact surfaces, observed in conjunction with deformation, caused by expansion of surface crazing.

Vesiculation: Formation of interconnected bubbles within obsidian specimen due to release of volatiles, specimen metamorphism to a foam-like mass.

Fire Fracture (field observation): Rapid thermal fracture of specimen (presumably due to differential thermal stress), may initiate near an inclusion.

With the exception of vesiculation which occurs at 800°C +, specific temperatures ranges are not provided for each of the associated types of thermal alteration defined above. However, several of the researchers have observed that appreciable thermal alteration of obsidian occurs at temperature in the 450-550°C range. Overall, research pertaining to the thermal alteration of obsidian suggests the exposure to heat can significantly affect the morphological integrity of obsidian artifacts as well as the potential to derive obsidian hydration dates from affected specimens. As such the integrity of the archaeological record as it pertains to obsidian artifacts may be significantly affected during prescribe and wildland fires.

Thermal Alteration of Bone

Bone consists of two major components, an organic phase and an inorganic phase. The organic phase (35% of dry bone mass) consists largely of protein, mostly in the form of collagen (Posner and Belts 1975). The inorganic phase is composed of mineral, mostly hydroxyapatite in microcrystalline form (Ortner et al. 1972). Thermal alteration of bone can significantly affect both components through chemical reaction and physical transformations. Shipman et al. (1984) have summarized the major observable changes that occur in bone when it is exposed to heat: 1) change in bone color; 2) change in the microscopic morphology of bone surfaces; 3) changes in the cystalline structure of bone; and 4) bone shrinkage. The degree of change in bone due to thermal alteration is dependent on the temperature at which bone is exposed, the duration of exposure, position of bone in relation to heat source, bone composition, and bone size (Brain 1993; Herrmann 1977; McCutcheon 1992; Nicholson 1993; Shipman et al. 1984; Sillen and Hoering 1993; Stiner et al. 1995; Von Endt and Ortner 1984).

Based on controlled experimentation, thermal alteration of bone can be generalized into three basic processes; water loss, carbonate loss, and mineral sintering (Bonucci and Graziani 1975; Kizzely 1973; Shipman et al. 1984). In general, there exists a relationship between temperature and degree of thermal alteration as they relate to each of the two major components of bone. At lower temperatures (~ 100-600^{o}C), the initial effect of thermal alteration is concentrated in the organic phase. As temperature increases into the 600^{o}C range the organic phase is effectively burned away, and as temperatures approach 700^{o}C and beyond the inorganic phase is affected through the recystallization of hydroxyapatite and the eventual fusion of those crystals.

Thermal alteration of the organic phase is generally characterized by distinct alterations in bone color. Chemical reactions are accelerated two fold for each 10^{o}C rise in temperature at which bone is exposed (Von Endt and Ortner 1984). Heat-induced color changes in bone are attributed to alterations in the chemical composition of bone, the oxidation of organics, and thin films of carbon layers deposited on bone mineral (Bonucci and Graziani 1975; Grupe and Hummel 1991; Shipman et al. 1984). Based on experimental work several authors have made observations concerning the relationship between temperature and observed color change in bone (Brain 1981, 1993; McCutcheon 1992; Nicholson 1993; Richter 1986; Shipman et al. 1984). These studies indicate that the color of bone changes progressively with increased temperature, and that the color of thermally altered bone can provide a rough index of the temperature range that bone reached as a result of exposure to heat. Shipman et al. (1984) provide the most systematic and widely cited assessment of heat-induce color alteration of bone. The researchers observed that heat-induced color alteration can be divided into five stages: stage 1 (20- <285^{o}C), neutral white/pale yellow; stage 2 (285- <525^{o}C), red brown, very dark grey-brown, neutral dark grey, and reddish yellow; stage 3 (525- <645^{o}C), neutral black dominant with some medium blue and reddish-yellow; stage 4 (645- <940^{o}C), neutral white dominant with some light blue-grey and light grey; stage 5 (940^{o}C+), neutral white with minimal medium grey and reddish-yellow. The range of colors reported in this study and others reflects the differential combustion of the organic component within a particular temperature range. Dark colors, particularly black, are related to the carbonization of collagen. Carbonized bone with a blackened or charred appearance is likely to have reached a temperature in the 250-550^{o}C range. Grey is associated with the final stages of organic component combustion. At temperatures of 600^{o}C and beyond the organic component is completely burned away resulting in calcination and a neutral white, chalky appearance.

Changes in the microscopic morphology of bone surfaces, its crystalline structure, and bone shrinkage due to thermal alteration are largely related to observable changes in the mineral phase of bone. Heat-induced change in the microscopic surface morphology of bone has typically been observed using Scanning Electron Microscopy (SEM) (Bonucci and Graziani 1975; McCutcheon 1992; Nicholson 1993, 1995; Shipman et al. 1984), and standard light microscopy (Brain 1993; Herrmann 1977; Nicholson 1993; Richter 1986). Shipman et al. (1984) provide the most succinct summary temperature dependent micro-morphological change: stage 1 stage 1 (20- <185^{o} C), normal bone texture observed, surface undulating but intact; stage 2 (185- <285^{o} C), surface increasingly irregular, tiny pore and fissures present, but surface intact; stage 3 (285- <440^{o} C), bone surface becomes glassy and smooth, patterned cracking appears; stage 4 (440- <800^{o} C), bone surface highly particularized; stage 5 (800- <940^{o}), particles melt and form larger polygonal structures. The results of each of the studies cited indicate that heat-induced change in the surface morphology of bone may be summarized into three general temperature dependent processes; carbonization, cracking, and eventual recrystallization.

The conditions under which the recrystallization of hydroxyapatite occurs have been investigated through the use of x-ray diffraction (XRD) (Bonucci and Gaziani 1975; McCutcheon 1992; Shipman et al. 1984). These researchers have shown that heat causes hydroxyapatite crystals to increase in size as temperature increases. The major change in crystal size is observed between 525-645^{o}C, and at temperatures above 645^{o}C larger hydroxyapatite crystals begin to expand at the expense of the smaller crystals until there is eventual fusion at temperatures above 800^{o} C. Heat-induced changes in hydroxyapatite crystal size can also affect macro-level morphological change through bone shrinkage and deformation (Buikstra and Swegle 1989; Herrmann 1977; Shipman et al. 1984). These studies suggest that observable changes in metric values and overall morphology of thermally altered bone will occur at temperatures above 700^{o}C.

Overall, archaeology's interest in thermally altered bone encompasses a broad range of archaeological phenomena from cremations to post-depositional processes. The most common issue related to the thermal alteration of archaeological bone relates to the desire to differentiate whether or not bone has been heated as a result of human intention. Experimental research directed at addressing these issues can be divided into three general categories; controlled laboratory experimentation, actualistic field research, or a combination of both. Laboratory experiments are generally characterized by making systematic observations of the effects of differential heating on the various structural and biological components of bone (Nicholson 1993, 1995; McCutcheon 1992; Richter 1986; Shipman et al. 1984; Taylor et al. 1995). Field experiments are also generally concerned with these questions, but the address them within the context of the replicated prehistoric campfires

(Bellomo 1991; Bellomo and Harris 1990; Brain 1993; David 1990; De Graaff 1961; Gilchrist and Mytum 1986; Nicholson 1995; Robins and Stock 1990; Spennemann and Colley 1989).

In addition to an interest in the cultural thermal alteration of bone, archaeologists have also become interested in studying the how burned bone and shell are affected by taphonomic processes (Knight 1985; Pearce and Luff 1994; Nicholson 1992; Robins and Stock 1990; Stiner et al. 1995). The main topic of interest here generally surrounds the survivorship potential of remains after thermal alteration. Most researchers are interested in the potential for differential destruction/survivorship between species and experimental conditions. In sum, these studies suggest that thermal alteration does significantly affect bone strength. Reduced bone strength was shown to have differential effect between species and skeletal element. Heat-induced change is an important taphonomic process that archaeologists need to consider when making inferences about site formation processes and human paleoecology.

Experimental research aimed at addressing issues related to cremation of human remains have generally been concerned with establishing the condition of bone prior to cremation (dry or fresh), and accounting for the effect of shrinkage when determining population estimates from cremated human remains (Baby 1954; Binford 1963; Buikstra and Herrmann 1977; Krogman 1939; Merbs 1967; Mckinley 1983; Ramrakhiani and Datta 1980; Swegle 1989; Thurman and Willmore 1981). Through experimentation, these researchers have shown that, when burned, dry bone will generally exhibit superficial checking and deep longitudinal cracking, and fresh bone will exhibit deep checking, deep transverse cracking, and warping.

While there is a considerable body of literature surrounding the thermal alteration of bone from cultural context, research concerning the post-depositional thermal alteration of bone is more limited (e.g., Bellomo 1991; Bellomo and Harris 1990; Bennett 1999; David 1990; De Graaff 1961; Sayler et al. 1989). David (1990) has shown that bone burned during an Australian bush fire (20-30 seconds flaming combustion, no temperature data) became carbonized and showed superficial cracking and longitudinal collapsing of the mid-shaft. Bellomo and Harris 1991 and Sayler et al. 1989 have shown that grassfire will generate minimal thermal alteration of surface bone generally consisting of carbonized color alteration and minor charring. Thermal alteration of subsurface bone as the result campfires can also be demonstrated (Bennett 1999; De Graaff 1961; Stiner et al. 1995). Campfires can reach temperatures in excess of 800^{o} C, and it has been shown that bone buried as deep as 10cm below campfire can show significant thermal alteration. The degree of thermal alteration is dependent on the depth of burial beneath the heat source and the heat transfer and retention properties of the sediment. Other important variables include the pre-burn condition of bone as well as species and skeletal element represented. It is unlikely that significant thermal alteration of subsurface bone will occur during natural fires. Sayler et al. (1989) have shown that while surface bone is moderately affected by prairie fire, bones buried as shallow as 2cm are not likely to be susceptible to significant thermal alteration. No data exists on subsurface thermal alteration of bone during natural fire in heavily fueled area such as forest.

Thermal Alteration of Ceramics

Simply by nature of their manufacture and use, archaeological ceramic materials are generally resistant to thermal alteration under moderate thermal gradient. At the time of manufacture, most prehistoric pottery was fired at temperatures in the 400-600°C range (Cogswell et al. 1997; Colten 1951; Feathers et al. 1998; Goodyear 1971; Heimann and

Franklin 1979; Kaiser and Lucius 1989; Rice 1987; Roberts 1963; Rye 1981; Shepard 1956; Tite 1969; Ziad and Roussan 1999). Under prescribed and wildland fire conditions, prehistoric ceramic materials should remain relatively stable until temperatures climb beyond original firing temperature and/or the temperature gradient becomes excessive and induces significant thermal stress. Historic ceramic materials such as porcelain and china are fired at temperatures of 1280-1400°C, and beyond (Rice 1987). However, these materials are manufactured to withstand significant thermal stress due to quality controlled manufacture and high firing temperature. Although, thermal stress in modern ceramics has received attention from several researchers in the ceramic industry (e.g., Amberg and Hartsook 1946; Buessem 1955; Chandler 1981; Coble and Kingery 1955; Crandall and Ging 1955; Davidge and Tapppin 1967; Grimshaw 1971; Hasselman 1969; 1970; 1983; Kingery 1955; Salmang 1961), it is unlikely that prescribed and wildland fire conditions would significantly affect these material in archaeological contexts.

The archaeological literature does offer some useful information regarding the thermal alteration of prehistoric ceramic materials within both the context of laboratory experimentation and from post-fire field observation. Materials science investigations into the thermal properties and thermal failure properties of prehistoric pottery offer important background information regarding the potential for thermal damage of ceramic materials (Bronitsky 1986; Bronitsky and Hamer 1986; Schiffer 1990; Schiffer et al. 1994; Young and Stone 1990). In general, thermal fracture of pottery occurs as the result of tensile or compressive stress generated by thermal gradient that exceeds the strength of the ceramic body. Essentially, differential thermal expansion or contraction within the body will elicit thermal fracture if the thermal stress is sufficiently greater than that which the structural components of the body can withstand. Important variables affecting this process include the coefficient of thermal expansion, thermal conductivity, temperature differential, and temperature gradient (Hasselman 1970; Kingery 1955; Rice 1987). In addition, Schiffer et al. (1994) have reported that thermal spalling occurs were steam pressure produces sufficient stress to exfoliate elliptical portions of ceramic surfaces, particularly where irregularities in the surface are present.

Forms of thermal alteration observed for ceramic materials that have been burned over during wildland fire include; thermal fracture, thermal spalling, combustion of organic paint, and oxidation or re-firing resulting in subsequent color alteration (Burgh 1960; Lentz et al. 1996; Switzer 1974). For the various types of Southwestern pottery sherds (particularly black-on-white), some researchers have attempted to document the conditions under which these forms of thermal alteration occur using laboratory and field experimentation. Through field experimentation, Oppelt and Oliverius (1993) have demonstrated that the application of fire retardant foam during burning will induce thermal shock among Mesa Verde Pottery sherds. However, the experiment did not document the potential for thermal fracture or spalling of sherds during combustion of natural fuels alone. Through laboratory experimentation using a muffle furnace, Bennett and Kunzmann (1985) observed heat-induced color alteration of ceramics at temperatures above 500°C in which redware varieties can change to a darker hue, and black-on-white wares will change to a “slightly buff” color due to the oxidation of iron minerals. Under laboratory conditions, other researchers have also observed that black-on-white sherds can oxidize to resemble redware (Burgh 1950; Colten 1953; Shepard 1956). Bennett and Kunzmann (1985) also suggest that the pigmented design on black-on-white sherds is stable under high temperature if the paint is mineral based, but may combust and fade significantly if the paint is organic based. This experiment produced only one occurrence of thermal spalling on a black-on-white sherd at a maximum temperature of 500°C, and one incidence of surface cracking on a redware specimen at 600°C. This is likely due to the limited potential for extreme thermal gradient produced within the muffle furnace as compared to a natural fire where the rate of heating and cooling would likely be more severe.

In addition to potential physical alteration of pottery sherds during natural fire, thermoluminescence dating of affected sherds may also be confounded as a result of heating during the fire. Luminescence signals in pottery are generally not affected by heating where the temperature is less than 250°C (Aitken 1985). However, the potential for wildland fire to generate soil surface temperatures above this threshold is quite probable. Theoretically, then, the TL signal of sherds burned during wildland fires may be altered depending on temperature, rate and duration of heating experienced by the specimen during the fire. Rowlett (1991) and Rowlett and Johannessen (1990) demonstrated that wildland fire can change the TL reaction for pottery sherds. Here the researchers sampled specimens burned during a wildland fire at Bandelier National Monument, New Mexico. Two specimens from surface contexts exhibited age underestimations of 24%. Although the scope of this project was limited, it illustrates that potential for wildland fire to negatively impact the validity of use TL techniques to date sherd from surface contexts where wildland fires have occurring in the recent or distant past.

Thermal Alteration of Metals and Glass

The literature surrounding the thermal alteration of metals under wildland fire and prescribed fire conditions is quite limited. Traylor (1990) refers to anecdotal accounts of automotive steel undergoing thermal deformation during severe wildland fire. In addition, Sayler et al. (1989) observed the partial melting and deformation of lead during prescribed burns in mixed grass prairie fuels. Metals common to the archaeological record such as iron, steel, tin, brass, copper, and lead do have established melting points at which significant damage could be predicted given sufficient fire intensity and energy output. The established melting points for these metals are as follows: iron (1275-1535°C), steel (1250-1480°C), tin (232°C), brass (900-930°C), copper (1083°C), lead (327°C) (Perry and Green 1984). Based on this information, tin and lead artifacts will likely be the most susceptible to melting during natural fire, other metals with higher melting points could be significantly affected only under conditions of severe fire intensity.

Archaeological metals, are of course, generally in a corrosive state in which electrochemical processes and ions create chemical compounds that adhere and bond to metal surfaces, and over time, may penetrate deep within the structure of metal objects (e.g., rust) (Hoff 1970; Organ 1976; Waite 1976). The extent to which exposure to fire affects corroded metal is not well documented; however, Engle and Weir (1998; 2000) have demonstrated that breaking strength, elongation, and ductility of new and corroded barbed wire is not significantly affected by exposure to grass fire. Schiffer (1987) suggests that corrosion on metal surfaces can serve as a protective film in archaeological contexts. Of particular interest, Schiffer also notes that if the coefficients of thermal expansion of the corrosive file and the metal are significantly different, thermal cycling could initiate cracking that could result in perpetuation of corrosion within the metal object. It is possible the archaeological metals subject to natural fire conditions could be affected heat-induced cracking and subsequent internal corrosion. In sum, then, archaeological metals subjected to wildland fire may be impacted by natural fire immediately due to melting and deformation, and over-time due to the potential increased internal corrosion.

Glass consists of three primary elements, silica, soda or potash, and lime or magnesia (Goffer 1980). The formation of glass is accomplished through fusion and cooling of its major constituents (Goffer 1980; Havlác 1983). The established melting point of glass is 750-870°C. Glass is essentially a supercooled liquid that performs as a solid, and is therefore, subject to thermal stress (DeHann 1997). Thermal stress caused by uneven heating will induce fracturing of glass when internal stresses exceed the tensile strength limit of glass (DeHann 1997; Lentini 1992). Thermally altered glass may exhibit straight fracture lines, crazing, shattering, and melting depending on fire conditions (DeHann 1997). As such, archaeological glass will be highly susceptible to thermal alteration under natural fire conditions given that the heat energy released by the fire is sufficient to induce significant thermal stress and/or melting.

Fuels, Combustion, and Heat Transfer

The ignition and combustion of organic fuels is largely a function of the fuel's surface to volume ratio and mass (DeBano et al. 1998). Fine fuels ignite, combust, and produce heat quickly (high combustion efficiency), whereas, heavier fuels tend to ignite, combust, and produce heat more slowly and uniformly low/moderate combustion efficiency) (DeBano et al. 1998). Important variables associated with fuels are loading, size and arrangement, composition, and moisture content (Rothermel 1972). These variables are also conditioned by environmental variables occurring during combustion such as temperature, wind speed and direction, relative humidity, slope and aspect, fire behavior, etc. (Chandler et al. 1983; DeBano et al. 1998; Pyne et al. 1996; Rothermel 1972; Whelan 1995; Wright and Bailey 1982).

Concerning the impact of wildland fire on archaeological resources, some important variables to consider are the total amount to heat (energy) produced, and the proportion of that energy which is transmitted to the mineral soil surface and within the mineral soil. Heat transfer can take the form of radiation (transfer via electromagnetic waves), convection (via the mixing of fluids), or conduction (via molecular activity within or between substances in contact) (Drysdale 1985). The dominant form of heat transfer downward from surface fuels to the duff layer (if present) and eventually the mineral soil is radiation (DeBano et al 1998). DeBano (1974) estimates that only 10-15% of energy released during the combustion of surface fuels is transmitted downward into the duff and/or mineral soil. If the duff is ignited and begins to combust (smoldering combustion), 40-73% of the heat may be transferred to the mineral soil (Hungerford and Ryan 1996). Burning duff can produce mineral soil temperatures of >350˚C for periods extending over several hours (DeBano et al. 1998). When no duff is present, heat energy is transferred directly from surface fuels to the mineral soil via radiation. The amount of heat transfer is variable and dependent on fuel loading, type, size and arrangement, etc. (Rothermel 1972). Within the mineral soil, heat is transferred via conduction and convection of hot gasses through the soil matrix (after water is vaporized ~100˚C) (Campbell et al. 1995; Campbell et al. 1994; DeBano et al. 1998). However, significant surface heating does not necessarily elicit high levels of soil heating due to thermal conductivity characteristics of soils (Frandsen and Ryan 1986; Hartford and Frandsen 1992; Nidal et al. 2000).

The proportion of heat energy that is transferred from organic fuels (surface or duff) to archaeological materials is dependent on the proximity of the artifact to the fuel as well as the multitude of variables associated with fuels and fire behavior. An artifact deposited on the contact between the mineral soil surface and combusted fuels will be subjected to a greater transmission of heat energy as compared to an artifact deposited 5cm beneath the mineral soil. Mineral soil and duff (non-combusted) insulate against heat transfer of combusted surface fuels. However, if there is a heavy duff concentration that ignites and begins to combust the heat energy transfer downward to the mineral soil surface can be significant. Similarly, if heavy combusted surface fuels (logs, etc.) are present, the transfer of heat energy towards the mineral soil may also be significant regardless of the presence of a duff layer. Artifact deposited greater than 5cm beneath the soil surface will likely be well insulated against radiant and conductive heat energy under most natural fire conditions.

The manner in which an artifact absorbs and is affected by heat energy is largely dependent on the physical composition of the artifact, and the thermal conductivity associated with its composition. Obviously, certain artifacts classes will be affected more significantly compared to others. For example, it requires a substantial amount of heat energy to significantly affect lithic artifacts, whereas, archaeological materials with organic composition such as bone may be affected by much lower levels of heat energy.   Thus, the important variables to consider when assessing the impact or potential impact of wildland fire or prescribed fire on archaeological materials are; 1) fuel type, 2) fuel load, 3) fire behavior, 4) proximity of artifacts to fuels, and 5) artifact class. In the following chapters, these variables are studied under a variety of controlled experimental conditions as well as during field recording of burned archaeological sites.

CHAPTER 2
THE IMPACT OF PRESCRIBED BURNING ON ARCHAEOLOGICAL RESOURCES

Introduction

Prescribed fire is an increasingly common land management practice utilized by public land agencies to reduce hazardous fuels and manage vegetative and wildlife communities. Moreover, given the severity of wildland fires in the Western United States during 2000 and 2002, it is probable that the use of prescribed burning to reduce fuel loads will become even more prevalent in the future. The impact of prescribed fire on archaeological resources has received the attention of archaeologists for approximately twenty years (Bennett and Kunzmann 1987; Benson 2002; Brunswig et al. 1995; Deal and McLemore 2002; Green et al. 1997; Halford and Halford 2002; Hanson 2001; Hester 1989; Jackson 1997; Kelly and Mayberry 1980; Lissoway and Propper 1990; Pilles 1982; Sayler et al. 1989 (see also Picha et al. 1991); Scott 1979; Smith 2002; Solomon 2002). Several researchers have assessed the potential impact of prescribed fire on cultural materials through field-based experimentation performed in conjunction with prescribed fires. Brief summaries and discussions of several relevant published research projects are provided below.

Kelly and Mayberry (1980) conducted one of the first research projects involving field experimentation to investigate the effects of prescribed fire on archaeological materials. The report itself is quite limited; however, the basic methodology consisted of establishing 5x5m test plots in which “artifact clusters” were placed on the sediment surface. The plots, six in total, were burned during prescribed fires in mixed conifer and sequoia-white fir environments (sparse understory and light ground fuels). Temperature measurement was attempted using temperature sensitive pellets and pyrometric cones; however, neither method was successful. Thermal alteration of the experimental artifacts was limited to "carbon smudging", and the diagnostic attributes of each specimen were not significantly altered during the experiment. The authors conclude that, cool burning prescribed fires are likely to have a limited impact on the diagnostic characteristics of surface artifacts. The incomplete nature of this report makes it difficult to ascertain specific information regarding the research methodology (e.g., the type of artifacts used, method of artifact analysis, fire behavior, etc.). The only specific information regarding artifact type was the inclusion of obsidian flakes that were submitted for obsidian hydration testing post-fire. The results of the obsidian hydration analysis were reported to be "inconclusive." The report, however limited, is nonetheless, a seminal contribution in the area of field-based experimentation and the potential impact of prescribed fire on archaeological resources.

Sayler et al. (1989) (see also Picha et al. 1991) conducted a more systematic investigation focusing on the impact of prescribed fire in prairie fuels on a range of archaeological materials common to the Knife River Indian Villages National Historic Site, North Dakota. Their research methodology consisted of placing experimental artifacts in 10x10m burn plots, both at the sediment surface and 2cm subsurface. Experimental artifacts included non-flint cobbles, Knife River flint cobbles, Knife River flint flakes, Knife River ware pottery sherds, cow bone, mussel shell, glass beads, lead sinkers, wood segments, and wood charcoal. Pre-fire and post-fire descriptive information regarding artifact dimensions and color (Munsell values) were recorded. During burning, maximum temperature data was measured at 10cm and 2cm above the soil surface using temperature sensitive crayons. In total, four contiguous 10x10m burn plots were ignited on two separate occasions, exposing approximately 1100 experimental artifacts to prescribed fire conditions. Mixed prairie grasses and buckbrush dominated fuel composition in the burn area, although the fuel load in each plot was variable.

The results of the experiment showed that the most pervasive form of thermal alteration observed was “scorching”, which refers to the presence of a combustive residue deposits on the surfaces of artifacts. Artifacts with organic components such as bone, shell, and wood, exhibited a combination of “scorching” and “charring”, the later refers to the partial combustion of organic component of the specimen. These two forms of thermal alteration resulted in shifts to darker Munsell values for most specimens, which the researchers define as “color change”. Significant forms of thermal alteration such as thermal fracturing and deformation/melting were observed at low frequencies. One flint cobble exhibited thermal spalling, approximately 11% of flint flakes exhibited potlid fracturing, two glass beads sustained partial melting, seven lead sinkers exhibited melting, and shell specimens sustained structural and morphological alteration. In general, the greatest degree of thermal alteration was observed for artifacts from Plot 4, which was characterized by the greatest fuel density. Maximum temperatures recorded at 2cm and 10cm above the soil surface for all plots ranged between 316-399°C, and flaming combustion within the plots was estimated at between 30-60 seconds. Subsurface artifacts were largely unaffected during the experiments. Soil temperatures, measured with digital thermometer prior to ignition and immediately following cessation of flaming combustion, were elevated only 2-4°C over baseline values.

The authors conclude that the impact of prescribed fires in prairie fuels will be insignificant for subsurface archaeological materials buried greater than 1cm beneath the mineral soil surface. They also predict that all artifacts positioned on the soil surface will become blackened due to scorching (combustive residue deposit) with organic materials sustaining the greatest degree of thermal alteration due to a combination of combustive residue deposition and partial combustion. Moreover, significant forms of thermal alteration such as thermal fracturing and structural change will be significantly less severe for lithic materials, pottery sherds, and other inorganic artifacts types as compared to organic materials. They also conclude that prescribed fire in prairie environments is unlikely to produce thermally altered artifacts that might be confused with materials from archaeological contexts such as fire-cracked rock and calcined bone.

This experiment is an important contribution to the study of the impact of prescribed fire on archaeological resources. The methodology used is the most systematic and most comprehensive available in the fire effects literature. However, one weak point in the experimental design relates to the method of temperature measurements. Maximum temperatures were recorded using temperature sensitive crayons wrapped in aluminum foil. This method produced only two maximum temperatures for each plot, one at 2cm above the soil surface and the other at 10cm above the soil surface. These temperature data are quite limited in that the method does not provide sufficient data on rate of heating and duration of heating. Moreover, temperature data were taken only at one point within each of the four plots, which does not account for variation in fire intensity within and between the plots. The use of a data logger and thermocouple system would have provided more detailed temperature data, which in turn could have been correlated to variability in artifact thermal alteration between each plot. Nonetheless, this experiment generated important information regarding the impact of prescribed fire in prairie fuels on various artifact classes, and remains one of the most comprehensive studies available on the subject.

Brunswig et al. (1995) conducted an experiment that essentially replicated the study performed by Sayler et al. (1989). Using the same research questions and similar methodology, Brunswig et al. (1995) carried out an experiment focused on assessing the impact of prescribed fire on archaeological resources in a high plains short-grass prairie environment. Two 4x4m burn plots "salted" with experimental artifacts were used in the study as well as two 4x4m plots at actual archaeological sites located within the prescribed burn area. Experimental artifacts included materials common to archaeological sites in the area such as quartzite and chert projectile points, quartzite and agate scrapers, quartzite flakes and cores, Plains Kansas pottery, deer antler, and cow bone. The researchers hypothesized that prescribed burning in a heavily grazed short-grass prairie environment would have a "minimal and short-lived" impact on the experimental artifacts and actual archaeological materials located within the burn area. It should be noted that no method of temperature measurement was implemented during the experiment.

The results of the experiments fully supported the "minimal-impact" hypothesis put forth by the researchers. Thermal alteration of artifacts was predominantly limited to combustive residue deposition on artifact surfaces. The only exceptions were limited evidence of partial charring and slight cracking of antler and bone specimens. Overall, no significant forms of thermal alteration such as thermal fracturing was observed. The authors conclude that the light fuel load compounded by cool and moist burning conditions were the most significant variables affecting the minimal impact of the burn on archaeological materials. They further suggest that, in general, prescribed fires in grassland environments are likely to have a limited impact on archaeological resources.

The results of this experiment are roughly consistent with those reported by Sayler et al. (1989). The major exception being the potlid fracturing of Knife River flint flakes, and shell disintegration observed by Sayler et al. The validity of the results presented by Brunswig et al. is, however, diminished due to the omission of temperature recording in the experimental design and information regarding fuel loads in the burn areas. Presumably, the slight fuels and cool moist conditions during the burn significantly limited the amount of heat energy produced by the fire, perhaps limiting maximum surface temperatures to the 100-200°C range. Fuel load and burn intensity during the Sayler et al. experiment was potentially greater, therefore, resulting in a slightly greater impact on experimental artifacts. To a certain degree, the Brunswig et al. experiment does support the assertion made by Sayler et al. regarding the impact of prescribed fire in grassland fuel on archaeological resources, and makes further contribution to the body of knowledge concerning this subject.

Several research papers exclusively focused on studying the effects of prescribed fire on obsidian, particularly obsidian hydration, are included in a recent volume compiled by Loyd et al. (2002). Deal and McLemore (2002) conducted two prescribed fire experiments in a Sierran yellow pine / black oak forest environment with the purpose of assessing the effects of prescribed fire on obsidian hydration bands. Research suggests that obsidian hydration bands begin to be affected by heating at approximately 260°C, become significantly affected at 427°C, and may be completely destroyed at temperatures exceeding 700°C (Benson 2002; Brunswig et al. 1995; Deal and McLemore 2002; Green et al. 1997; Halford and Halford 2002; Origer 1996; Smith 2002; Solomon 2002; Steffen 2002; Trembour 1990). The research design consisted of placing obsidian artifacts with previously established hydration bands in burn plots with variable fuel load (“light”, “woody”, and “log”). Temperatures were recorded at the soil surface and subsurface (-5-7cm) using a thermocouple and data logger system. This is an important component of the experimental design since most studies have only incorporated crude indicators of maximum temperature such as temperature sensitive crayons, pellets, and paints. Use of a thermocouple / data logger system allowed the researchers to generate coarse time and temperature curves from which heating rate, duration, and maximum temperature could be derived.

The first experiment was conducted in an environment characterized by a considerable build up of hazardous fuels with an estimated fuel load of approximately 16-31 tons/acre (5888-11,409 kg/ha). Due to a thick duff accumulation, surface temperatures reached maximum levels over a protracted period of 2.5 hours. The peak surface temperature associated with log fuels was approximately 520°C, woody fuels 310°C, and light fuels 305°C. Subsurface temperature reached maximum levels of 73-67°C over an extended period of 6.5 hours. The results of this experiment showed that in lighter fuels hydration bands were altered for 56% of the sample, woody fuels 67% of the sample, log fuels 78% of the sample, and subsurface 44% of the sample (N=27).

The second experiment was conducted during the spring in an area where hazardous fuels had been reduced by periodic prescribed burning (estimated fuel load 4 tons/acre, 1472 kg/ha). The same experimental method used during the previous experiment was also implemented here. Peak temperatures recorded during the experiment ranged from approximately 475°C for log fuels to 137°C and 79°C for woody and light fuels respectively. Temperatures peaked rapidly within minutes and were sustained at high levels for 2-4 hours. The results of the experiment showed that 44% of the log fuel specimens, 11% of the woody fuel specimens, and 44% of the light fuel specimens exhibited altered hydration bands. Due to the lighter fuel load, alteration of hydration bands during this experiment were diminished during this experiment as compared to the previous where fuel load was heavier. In addition to alteration of hydration bands, 74% of the specimens from both experiments exhibited additional forms of thermal alteration such as surface sheen, pitting, and combustive residue deposition. Overall, the experiments demonstrate that fuel load, burn duration, and peak temperature are important variables affecting the alteration of obsidian hydration bands.

Solomon (2002) conducted a similar experiment in a Ponderosa pine / mixed conifer environment with an estimated fuel load of 3.5 tons/acre (1288 kg/ha). The experimental design consisted of placing obsidian artifacts, with previously determined hydration bands, at the soil surface within designated burn plots. Fuel compositions within the burn areas were variable to include a slash pile, log fuels, woody fuel, and light fuels. Maximum temperature data were recorded using heat sensitive temperature pellets placed beneath each artifact. This method is unlikely to produce accurate temperature readings since there is often a significant temperature differential between the upper and lower surfaces of an artifact during burning (see dissertation chapter 4). The results of the experiment show that temperatures at the soil surface did not exceed 101°C with the exception of the surface beneath the slash pile in which surface temperatures were estimated to have reached the 400-500°C range. Two obsidian specimens from the slash pile slot exhibited diffused hydration bands; however, none of the remaining specimens included in the study exhibited altered hydration bands. The author concludes that low intensity prescribed burns in Ponderosa pine / mixed conifer environments are unlikely to negatively affect obsidian hydration bands. Conversely, the author suggests that burning under slash pile fuel loads has a potentially greater probability of negatively affecting hydration bands. Although the method of temperature measurement used during this study is insufficient, the results further reiterate the important relationship between fuel load / fire intensity and potential thermal alteration of obsidian hydration bands.

Halford and Halford (2002) conducted a prescribed burn experiment in sagebrush fuels to assess the impact of burning in this fuel model on obsidian hydration bands. The experiment consisted of six 1x1m burn plots situated in variable fuel densities of heavy moderate and light in which 180 obsidian artifacts (with established hydration bands) were equally distributed across the plots and at variable soil depths (soil surface, -5cm, -10cm). Temperature data were recorded using temperature sensitive pellets of various melting thresholds ranging between 149-843°C. In addition a digital thermometer paired with two thermocouples was used to measure temperature gradient in Plot 1 during the burn.

The prescribed burn was conducted in late fall under cool and moist conditions, which diminished fire intensity and the potential for the fire to carry itself across the burn area. The results of the experiment show that in Plot 1 (light fuel) surface temperature peaked at only 85.2°C and subsurface (-5cm) temperature reached a maximum of only 6.2°C. In plots with heavier fuels, peak surfaces temperatures are reported to have reached approximately 300°C (temperature pellets). The impact of the burn on obsidian specimens was minimal, and generally limited to surface specimens from one heavy and one moderate fuel plot. For the heavy fuel plot, 40% of specimens are reported as exhibiting diffuse hydration bands, and in moderate fuel plot 10% of specimens were similarly affected. Due to the significant degree of inter and intra-plot temperature/burn intensity variability observed during the experiment, the authors conclude that, in sagebrush environments fuel density and the proximity of artifacts to fuels are important variables that potentially affect the thermal alteration of obsidian hydration bands.

Green et al. (1997) conducted a similar experiment during a prescribed burn in sagebrush fuels. The research methodology consisted of placing obsidian artifacts with established hydration bands in burn plots of variable fuel density (heavy, moderate, light). Temperature data were recorded by placing temperatures sensitive tablet beneath each artifact. The results of the experiments demonstrated that alteration of obsidian hydration bands is strongly associated with fuel load and burn temperature. The authors conclude that surface temperatures below 200°C are unlikely to produce diffuse or destroyed obsidian hydration bands.

Additional experimentation of this nature conducted in sagebrush fuels was performed by Benson (2002). In addition to assessing the impact of prescribed burning on obsidian hydration bands, the experiment included a second component that was focused on the potential for thermal alteration of chert artifacts. The experimental design consisted of subdividing a burn plot into heavy, moderate, and light subplots (three each) in which 90 obsidian artifacts and 90 chert artifacts were equally distributed at the soil surface. Soil surface temperature data were collected using an unspecified data logger and thermocouple system. The results of the experiment showed that surface temperatures in the heavy fuel subplots ranged between approximately 73-725°C (specific time / temperature curves are not provided) and that the hydration bands from all obsidian specimens were either diffuse or completely obliterated. Surface temperatures in the moderate fuel subplots ranged between 80-550°C and the hydration bands on 24 specimens were negatively affected. In the light fuel plots surface temperatures ranged between 37-440°C, negative affecting the hydration bands of 16 specimens.

The portion of the experiment focused on the potential for thermal alteration of chert artifacts is only vaguely discussed in the report. Specifically, the source of the chert material is not specified; no time / temperature data are provided for chert artifacts; and the extent of thermal alteration associated with chert artifacts is reported as "severely damaged" with little reference to specific observations. The only information provided is contained within the following statement; "All of the large and many of the medium size flakes shattered into tiny fragments. Many of the smaller flakes were structurally unchanged, but altered in other ways (p.100)". No further elaboration is provided. Based on the temperature data provided for the subplots, it is likely that the chert specimens were subjected to peak temperatures ranging between 440-725°C. These temperatures are well within the range necessary to induce significant thermal fracturing of chert (see dissertation chapters 3 and 4).

The author concludes that during prescribed fires where surface temperatures exceed 300°C, thermal alteration of obsidian hydration bands is likely to occur. However, the author suggests that duration of heating is also an important variable operating in tandem with temperature range. Again, the dynamic between fuel load, burn intensity, and potential thermal alteration of selected archaeological materials is reiterated.

Discussion

In sum, each of the research projects discussed above offers important contributions in assessing the potential thermal alteration of archaeological resources during prescribed fires. Nonetheless, several of the experimental designs share a common weakness, which is directly related to method of temperature recording. With the exception of Deal and McLemore (2002) and Benson (2002) temperature data were acquired using temperature sensitive products, which only provide a broad range estimate of maximum temperature. Excessive confidence was placed on the reliability of these products in actually establishing the peak temperatures at which individual artifacts were heated. Moreover, some researchers placed these products beneath artifacts during experiments, effectively estimating the maximum temperature beneath specimens, not on upper surface where temperature may be 50-60% greater (see dissertation chapter 4). In addition, most researchers failed to consider the potential for variable burn intensity and temperature with the spatially defined boundaries of individual burn plots. Where data loggers and thermocouples were used to establish time and temperature gradients within burn plots, the data are often coarsely measured over gross time intervals measured in 30-60 minute units. Capturing data points at shorter intervals such as 1-5 seconds would provide more detailed information regarding heating rate, duration, and peak temperature. Clearly, more reliable and detailed methods of temperature measurement are needed to accurately assess the impact of a given burn intensity/temperature on archaeological materials. Additional research that incorporates a wide range of artifact classes and a variety of prescribed burn fuel models is also necessary to further the base of knowledge acquired on the subject thus far. In order to address these issues, a series of prescribed burn field experiments were conducted. Information regarding the experimental design, fuel environment, and results are provided in the following section.

PRESCRIBED FIRE EXPERIMENTS

Field experiments performed in conjunction with prescribed burns were designed and implemented during the 2001 and 2002 field seasons. Experiments were conducted in a variety of fuel types during planned prescribed burns at Badlands National Park, Grand Teton National Park, Wind Cave National Park, Pike National Forest (Colorado Front Range), and Bureau of Land Management lands (northwestern Colorado). In addition, one experiment was conducted in the Pike National Forest during the Shoonover Fire , which at the time the experiment was implemented was a low-intensity wildland fire where conditions were analogous to those generated during a prescribed burn. Dominant fuel types in the environments where experiments were performed included: mixed grass prairie (Badlands National Park); mixed grass prairie / Ponderosa Pine (Wind Cave National Park); sagebrush (Grand Teton National Park); riparian/willow (Grand Teton National Park); mixed conifer, Ponderosa Pine / Douglas Fir (Pike National Forest); and piñon-juniper (Colorado BLM). The purpose of these experiments were to:

1. Observe surface and subsurface time/temperature gradients generated during prescribed fires in a variety of fuel models ranging from light (grassland) to heavy (mixed conifer).

2. For a specific fuel model, observe and document the effects of heat energy released during flaming combustion on a variety of archaeological material types common to the archaeological record.

3. Based on these data, provide broad guidelines for land managers regarding the potential impact of prescribed fire on archaeological resources given a specific fuel model and archaeological material type.

Research Design

The research design utilized during the prescribed fire experiments was influenced by that developed by Sayler et al. (1989), but adapted and refined to meet the specific goals of this project. The basic method used during the experiments consisted of establishing 2x2m or 1x1m burn units, divided into four $1m^2$ or $50cm^2$ quadrants in which clusters of experimental artifact were positioned at the mineral soil surface. The artifacts consisted of modern replicates or analogs of common prehistoric and historic archaeological materials. The artifact classes represented included mammal bone (various deer and elk elements), freshwater mussel shell (various species), lithics (chert and obsidian flakes), pottery (prehistoric replicates and unprovenienced black-on-white sherds), metals (copper, brass, lead), firearm cartridges (rifle/handgun), glass fragments (beverage containers), ceramics (white ware), beads (wood, glass), and wood (2x4inch pine scraps). Each quadrant within the burn plot contained a cluster of experimental artifacts representing the same range of material types. Thermal alteration assessments of artifacts were based on recording the range of thermal alteration attributes observed during post-burn analysis. Thermal alteration attributes included various degrees of alteration ranging from combustive residue deposits to thermal fracturing (definitions provided in Appendix 1, Data CD). Supplemental information regarding weather conditions, fuel load, and fire behavior were also recorded during each experiment. Experimental artifacts (N=832) were measured, weighed and assigned Munsell (2000) color values pre- and post-fire. Descriptive information and thermal alteration analysis of each artifact included in the study is provided in Appendix 1, located on the Data CD included with the dissertation.

In addition to the basic 2x2m burn plot experimental setup, four modifications of the design were also conducted over the course of the prescribed burn project. First, some prescribed burn experiments were performed where only surface temperature data was collected without the inclusion of experimental artifacts. These experiments were performed with the purpose of gathering additional time/temperature data in order to validate the data generated during previous experiments. The second modified design consisted of trials in which upper and lower surface temperatures of experimental artifacts were recorded during a prescribed burn in grassland fuels and during a low-intensity wildland fire in a mixed conifer environment. The third manipulation of the basic experimental design included a series of log burning experiments performed during a prescribed burn in mixed conifer fuels. These experiments were conducted to observe the range of soil surface temperatures generated beneath heavy fuels, and the effects of the heat energy release on lithic artifacts. The log burning experiments consisted of a 1x1m burn unit placed arbitrarily over downed, dead logs ranging in size from 10-30cm in diameter. Modern replicated lithic flaking debris was placed at the soil surface beneath the logs and subsequently burned, then later analyzed for thermal alteration attributes.

Time and temperature data during each experiment were recorded using two systems. The primary system, used for the majority of the project, consisted of an Omega OM-3000 portable data logger and six Type K hi-temperature inconel overbraided ceramic fiber insulated thermocouples (XCIB-K-1-2-25, 25ft length, Type OST male connector, probe style 1 termination) (Omega Engineering 2000). During burning, the data logger was housed in a fire/heat resistant case (Sentry security chest), which in turn was over-wrapped with heat reflective carbon cloth. The data logger was programmed to record temperature (°C) data points every 1second, 5 seconds, or 10 seconds depending on the fuel type and experimental situation. Thermocouples leads were placed at the mineral soil surface within the center of each quadrant, roughly at the center of the artifact cluster. Subsurface temperatures were also recorded by placing thermocouples at various soil depths ranging between 1-10cm depending on the fuel type. This data recording system allows for the generation of detailed time/temperature curves showing rate of heating, peak temperature, time at peak, and cooling rate via computer download from the data logger to a PC.

The secondary time/temperature recording system consisted of a portable data logger and thermocouple system developed and constructed by Jim Reardon at the USDA Intermountain Fire Sciences Laboratory (Missoula, MT). Here the temperature logger program was downloaded to the data logger box via PDA prior to initiation of the experiment. Thermocouples (K Type, ceramic overbraid) were placed on the upper and lower surfaces of experimental artifacts to assess the potential temperature differential between these two surfaces during a fire. The data loggers were buried approximately 20cm subsurface during burns to inhibit potential thermal damage. Post-fire the data were uploaded to the PDA, then downloaded to a PC for compilation and analysis. Data generated by both systems fill in crucial information regarding the range of temperatures and duration of heating generated by combusting fuels of various composition as well as the ability to associate these data with observable thermal alteration of experimental artifacts. Time and temperature data for each of the experiments conducted during the study are provided in Appendix 1, located the data CD. These comprehensive data were largely absent from previous research conducted during prescribed burns where only maximum temperature was roughly estimated using temperature sensitive products with standardized melting points such as crayons, pellets, and paints; and roughly correlated with thermal alteration of archaeological materials.

MIXED GRASS PRAIRIE EXPERIMENTS

Prescribed burning experiments in grassland fuels were conducted at Badlands National Park, which is located in southwestern South Dakota near the eastern margin of the Black Hills. The dominant vegetative biome in the area is mixed grass prairie. Research at the park was undertaken in early May 2001 in conjunction with a prescribed burn project focused on reducing the presence of an invasive grass species (smooth brome, *Bromus inermis*) and the promotion of native species. Research was resumed at Badlands National Park for 2002 in conjunction with the continuation of the previous project in April of 2002, and during an additional prescribed burn conducted during late April and early May of the same year.

2001 Badlands National Park Experiment

The 2001 experiment at Badlands NP included four burn plots, each of which contained approximately 50 experimental artifacts. Thermocouples 1-4 were placed on the soil surface within each $1m^2$ quadrants delineated within the 2X2m burn plots. Thermocouple 6 was placed 2cm below the soil surface at the approximate center of each burn plot to determine subsurface temperatures during the burn. The prescribed burn occurred in moist grassland fuels, predominantly smooth brome *(Bromus inermis*), with an estimated fuel load of approximately 4 tons per acre (1472 kg/ha).

Results

The time/temperature data for Plot 1 are summarized in Figure 2.1 (All figures are provided at the end of Chapter 2). These data show maximum surface temperatures ranging widely from 418.8-82.0°C. The 418.8°C value is clearly an anomaly compared to the other values for which peak temperatures were considerably lower. This irregular value may be due to a displaced thermocouple and/or the occurrence of flames coming into direct contact with the thermocouple sensor. Overall, surface temperatures peaked and fell to near baseline values within 7 minutes, with the greatest portion of heating occurring within the first 1 minute of combustion. Peak temperatures reached apex levels within 30-60 seconds, and were sustained at near maximum values briefly for only 10-15 seconds. Subsurface temperature (at –2cm) reached a maximum of only 25.8°C, an increase of only 15°C over the baseline value. The time/temperature curve for the subsurface thermocouple is characterized by low apex and is considerably more protracted compared to the curves generated by surface thermocouples. This suggests that subsurface heating at –2cm is minimal under the conditions observed during burning. Field notes on observed fire behavior are indicative of low fire severity. The flame front (backing fire) required approximately 3.5 minutes to pass across the 2x2m unit (40-60m per hr), and flame length was estimated at between 20-40cm.

The time/temperature data for Plot 2 are summarized in Figure 2.2. Surface temperatures within Plot 2 peaked and fell to near baseline temperatures within 10 minutes, with the greatest range of heating occurring within the first minute of the time and temperature curve. Maximum surface temperatures recorded for each quadrant of the burn plot varied moderately ranging between 235.0-106.6˚C. Peak temperatures were attained within 40-60 seconds, and remained elevated for a short duration (10-15 seconds). Time/temperature curves for each of the surface thermocouples are uniform in contour, suggesting consistent burning across the entire plot. The maximum subsurface temperature recorded was within the plot was 21.5˚C, which is only a slight increase over the 12.3˚C baseline reading. Fire behavior observations show that the flame front (backing fire) spread across the unit within approximately 2min38sec (40-60m per hr), and flame length was estimated at 20-40cm.

The time/temperature data for Plot 3 are summarized in Figure 2.3. These data show very uniform curves with peak surface temperatures ranging between 150.2-281.0˚C. Surface temperatures reached maximum levels within approximately 30-50 seconds and were sustained at elevated levels only briefly for approximately 10-15 seconds. The entire duration of heating from baseline, to peak, to return near baseline was approximately 11 minutes. The maximum subsurface temperature at –2cm was recorded at 22.7˚C, which represents a minimal 5.8°C increase over the baseline value. Observed fire behavior notation recorded the flame front (head fire) passing over the plot within approximately 2min7sec (300-1200m per hr), and estimated flame length ranging between 30-60cm.

The time/temperature data for Plot 4 are summarized in Figure 2.4. Maximum surface temperatures recorded within each quadrant varied widely from 321.2-61.6˚C. Thermocouple time/temperature curves for quadrant 1 and 3 are uniform in contour and similar with regard to peak temperature (250-300°C). Data from quadrant 2 and 4 contrast sharply compared to quadrants 1 and 3, showing low peak temperatures (60-70°C) and protracted curves. These data suggest that combustion within the burn plot was not consistent across all quadrants. Overall, peak surface temperatures recorded in Plot 4 peaked and fell to near baseline within 8 minutes with the largest proportion of heating occurred during the first

1 minute of combustion. The maximum subsurface temperature recorded within the plot was 34.6˚C, only a 13.3 °C increase over the baseline value. Fire behavior observations show the flame front (head fire) traversing the plot within approximately 2min (300-1200m per hr) with estimated flame length of 30-60cm.

In general, maximum surface temperatures between the quadrants delineated within each of the four burn plots varied considerably ranging between 418.8-61.6˚C. These temperatures were characterized by brief residence times in which peak and near peak values were sustained for only 10-15 seconds. The average maximum surface temperature recorded within each quadrant across all four burn plots was 195.8°C. Overall, time curves for each plot show that temperatures peaked precipitously, then fell rapidly to near baseline within 6-9 minutes. The steepest portions of the curves show that the majority of heating above 50 °C occurred within the first minute of combustion. In sum, the results of the grassland prescribed burn experiment indicated that surface heating during combustion was rapid but brief in duration.

Subsurface heating at –2cm during combustion of grassland fuels was negligible. Maximum subsurface temperatures for burn plots 1-4 ranged between 21.5-34.6°C. The average peak subsurface temperature across the four burn plots was 26.2°C, which was only an average increase of 10.9°C over baseline temperatures recorded prior to burning. These data suggest that 2cm of soil is sufficient to mitigate subsurface heating during cool-season prescribed burning in grassland fuels.

Post-burn analysis of over 200 experimental artifacts subjected to burning during the experiment show that the limited amount of heat energy produced by combusting grassland fuels did not generate significant thermal alteration of any artifact classes. No potentially detrimental thermal damage in the form of thermal fracturing, cracking, spalling, or deformation was observed (with the exception of melted plastic on the shotgun shells). The most significant type of thermal alteration observed occurred in the form of partial combustion/charring of organic specimens such as wooden beads, 2x4 inch pine scraps, and the organic component of some bone specimens (generally limited to upper edges of specimens where bone density was thin). Interestingly, the pine scraps, and wooden beads did not fully combust; only minor evidence of incomplete combustion on the upper surfaces and edges of these specimens was present.

Over the entire artifact sample, the only immediately discernable effect of burning was the discoloration of the upper surfaces of specimens in the form of an adhesive light brown combustive residue deposit, and minor blackening/charring along the upper edges of organic specimens. The combustive residue deposit is a highly nitrogenous condensate tar that forms on cool surfaces (i.e., artifacts) during a fire (Yokelson et al. 1997). This deposit ranged in color from golden brown to black depending on the extent of combustion of the tar deposit. The charred portions of organic specimens represent the byproduct of the pyrolysis and partial combustion of those materials, particularly wood specimens. DeBano et al. 1998:23, refer to this as “char”, a substance that is neither an intact organic compound nor pure carbon. In the instance of condensate tar deposition on artifact surfaces, it is likely that under natural conditions these deposits will weather from the surfaces of artifacts over time. In the laboratory, these deposits can be removed via vigorous scrubbing with water and a pumice soap solution. The charred portions of organic specimens; however, are permanent thermal alterations of the artifact structure that may, overtime lead to enhanced degeneration of these artifact classes.

In general, the impact of prescribed burning in grassland fuels on the experimental artifacts is generally consistent with similar experimental results reported by Sayler et al.

(1989) and Brunswig et al. (1995). Sayler et al. (1989) report pervasive "scorching" (combustive residue deposits) of all experimental artifacts as well as charring of organic specimens during prescribed burning in a prairie environment. However, the researchers did report potlid fracturing, lead deformation, and shell damage, of which no instances were observed during the present experiment. This is likely due to heavier fuel loading (buck brush) in two of the experimental burn plots set up by Sayler et al. (1989). The results of the present experiment show that although grassland fuels are homogeneous, there was a wide range of variability in the maximum surface temperature recordings between and within each of the burn plots. This is likely due to variable rates of combustion of fuels within each plot, and the possible occurrence of flames coming in contact with a thermocouple sensor. In addition, grassland fuels were not heavy enough to sustain high temperatures and long residence times. This is reflected in the recorded subsurface temperatures that were elevated only 10-15˚ over baseline in each of the 4 burn plots. Based on these observations, it is suggested that prescribed burning in mixed-grass fuels presents a minimal risk to surface artifacts, and little or no risk to subsurface artifacts.

2002 Badlands National Park Experiments

Field experimentation performed in conjunction with prescribed burning at Badlands National Park was continued in the spring of 2002 during the continuation of the roadside burn project and during the Pinnacles burn project. Experimentation during the roadside burn project consisted a research design using three burn plots similar to that outlined for the 2001 experiments. The only exceptions being that experimental artifacts were placed within Plot 1 only and no artifacts were included in Plots 2 and 3, only temperature data was collected within those plots. In addition, thermocouple placement was also slightly altered such that thermocouple 5 was placed –1cm subsurface, and thermocouple 6 was placed –2cm subsurface within quadrant 2 of each plot. Fuel loads were similar to those described during the 2001 experiment.

During the Pinnacles burn project, the same methodology was used for three burn plots with the exception that artifacts in Plot 1 were sprayed with fire retardant immediately after combustion had ceased within the unit to assess the potential for thermal shock during the application of fire suppressant foam. In addition, an experiment designed to assess the temperature differential on the upper (side facing atmosphere) and lower (side facing soil surface) surfaces of an artifact during prescribed grassland fire conditions was also conducted. The experiment consisted of attaching thermocouples (via binder clips) to the upper and lower surfaces of 3 artifacts (pronghorn [*Antilocapra Americana*] mandible, black-on-white pottery sherd, and Hartville Uplift chert flake). Ten trials were performed using the same three artifacts in each trial to observe the cumulative impact of repeated burning in grass fuels on the artifacts as well as the temperature differential between upper and lower surfaces of each artifact during the experiment. Digital photos were taken of each artifact beginning and following each trial. Fire behavior and fuel information were also recorded for each trial.

Results: Roadside Burn Project

Smooth brome (*Bromus inermis*) was the dominant fuel type during the roadside burn project. Time/temperature data for Plot1 are provided in Figure 2.5. These data show that maximum surface temperatures within the burn plot varied considerably from 67.0-256.6°C during combustion. Temperatures reached apex levels rapidly within approximately 30 seconds and were sustained at elevated levels only briefly for 10-15 seconds. Surface heating within the plot was relatively consistent with the exception of quadrant 1 in which peak temperatures were limited to the 60°C range. Overall, surface temperatures within the plot peaked and diminished to below 50 °C within approximately 7 minutes. Subsurface temperatures at –1cm increased from 6.3-30.5°C, and temperatures at –2cm increased from 6.2-12.4°C. Fire behavior observations documented during the burn show the flame front (backing fire) passing the 2x2m burn plot within approximately 2.5 minutes, and flame lengths ranging between 15-50cm. Time and temperature data indicate that the maximum amount of surface heating occurred within the 2.5-minute window.

Post-fire analysis of over 50 experimental artifacts from Plot 1 indicated that the impact of the burn on the artifacts was minimal. Overall, a light brown condensate tar deposit was pervasive across the upper surfaces of all specimens. Some bone and wooden bead specimens also exhibited minor charring on upper surfaces as well. However, no significant forms of thermal alteration such as thermal fracturing, spalling, or deformation was observed. These observations are consistent with those reported for the experiments conducted at Badlands National Park during the roadside prescribed burn in 2001. Moreover, the results of the Plot 1 trial further support the assertion that cool-season prescribed burning in grassland fuels will produce low peak surface temperatures characterized by brief residence times, which in turn, present a limited potential for significant thermal alteration of surface artifacts. In addition, subsurface heating generated by combusting fine fuels was minimal at depths of –1cm and –2cm further indicating that subsurface archaeological material are unlikely to be significantly affected during grassland prescribed burns.

Experimental artifacts were not included in Plots 2 and 3; only temperature data were collected during burning. Time/temperature data for Plots 2-3 are summarized in Figure 2.6. Data for Plot 2 show maximum surface temperatures varying considerably between 86.7-281.3°C. Heating within quadrants 1 and 3 was characterized by rapid ascent to peak temperatures and brief residence times. Surface heating within quadrants 2 and 4 was less severe and more protracted indicating inconsistent combustion within the plot. Subsurface temperatures at –1cm increased from 12.7-27.2°C, and temperatures at –2cm increased from 9.0-13.2°C. Fire behavior observations show that the plot was burned within 1.5 minutes via a flanking fire that generated flame lengths of 50-75cm. Consequently, the maximum duration of heat penetration at the soil surface was limited to this short window. Over the entire burn window, temperatures peaked and fell to below 50°C within approximately 4.5 minutes.

Peak surface temperature within Plot 3 varied between 72.3-196.9 °C. The time/temperature data for the plot show that surface heating was consistent with the exception of quadrant 2 where peak temperatures were limited to 72.3°C. Surface heating within the plot was precipitous and brief with the greatest proportion of heating occurring within the first minute of combustion, and the entire duration of heating in excess of 50°C lasting approximately 4.5 minutes. Subsurface temperatures at –1cm increased from 11.3-19.3 °C, and temperatures at –2cm rose from 12.8-20.9 °C, indicating minimal subsurface heat penetration. Fire behavior observations show the flame front (head fire) crossing the unit within minute with flames lengths ranging between 50-150cm.

Results: Pinnacles Burn Project

An additional experiment consisting of three burn plots was conducted at Badlands National Park in conjunction with Pinnacles burn project during the spring of 2002. The dominant fuel type within each of the three plots was Western Wheat grass (*Agropyron* smithii). The experimental method was similar to that described for the 2002 roadside project experiment with the exception of the method used for Plot 1. During this trial fire suppressant foam was applied to the unit immediately after flaming combustion had ceased. Experimental artifacts were placed in quadrant 1 only. Here eight artifacts (2 obsidian flakes, 1 Hartville Uplift chert flake, 1 Hartville Uplift chert nodule, 2 black-on-white potter sherds, and 2 deer *Odocoileus sp.* appendicular elements) were placed at the soil surface to observe the impact of abrupt temperature changes on various artifact classes.

Time/temperature data for Plot 1 show that maximum surface temperature within the plot varied considerably, ranging from 48.5-289.0 °C. Temperatures at –1cm subsurface increased from 8.6 –35.3 °C, and temperatures at –2cm increased from 8.9-12.2 °C. Fire behavior observation recorded the flame front (flanking fire) crossing the plot within 2.5 minutes. Fire suppressant foam was applied to the unit immediately after flaming combustion has ceased. This is reflected in the time-temperature curves for each thermocouple, which show sharp and erratic declines in temperature within 2 minutes versus the typical 4-8 minute range observed in previous experiments. The abrupt change in temperature, however, did not have a significant impact on the experimental artifacts. None of the artifacts exhibited fracturing or spalling that is characteristic of thermal stress induced by irregular heating and rapid change in temperature. This is most likely do the fact that maximum surface temperatures were low and of minimal duration during combustion within the plot. Although temperatures did drop sharply, it was not sufficient to create tensile stresses that could initiate thermal fracturing within the artifacts.

Neither experimental artifacts nor fire suppressant foam were applied during burning within Plots 2 and 3; only temperature data were recorded. Time/temperature data for plots 2 and 3 are summarized in Figure 2.7. Maximum surface temperatures within Plot 2 were rather low, ranging from between only 70.9-94.0 °C. Subsurface temperatures at –1cm increased from 3.3-35.6 °C, and subsurface temperatures at –2cm increased from 6.5-13.5 °C. Overall, surface temperatures within the plot peaked and fell to below 50 °C rapidly within 2.5 minutes. Fire behavior observations recorded the flame front (head fire) crossing the burn plot within less than 1 minute. The low peak surface temperatures and short residence times can be attributed to the flame front flashing through the fuels quickly as the result of wind and a slight 5% slope.

The experimental design was altered for Plot 3. Here a juniper branch (approx 2m long x 4-8 cm diameter) was added to the unit by the experimenter. Thermocouples 1-4 were placed at the surface within each respective quadrant, and thermocouples 5-6 were placed directly beneath the juniper branch. The burn plot was burned via a head fire that crossed the unit in less than 1 minute with some residual flaming combustion occurring for 2.5 minutes. The Juniper branch did not combust, and was only slightly charred. Maximum surface temperatures ranged between 60.0-417.5 °C, and maximum temperatures recorded beneath the juniper ranged only between 27.5-87.5 °C. The peak temperature value for thermocouple 3 of 417.5 °C is anomalous, and may be the result of the thermocouple coming out of position at the soil surface and coming into direct contact with a flame.

Artifact Surface Temperature Experiment

The final component of the Pinnacles prescribed burn project consisted of an experiment designed to assess the temperature differential between the upper and lower surfaces of artifacts during burning in grassland fuels. Thermocouples were attached to the upper and lower surfaces of 3 artifacts (a pronghorn mandible, a black-on-white pottery sherd, and a Hartville Uplift chert flake). In total, ten trials were performed using the same three artifacts in each trial.

The results of the ten trials show maximum temperatures on the upper surfaces of experimental artifacts varying broadly between 37.4-268.9°C; however, the average maximum upper surface temperature for the overall sample was 189.3°C. Maximum temperatures recorded on the lower surfaces of the same artifacts also varied considerably ranging between 31.4-191.3°C. The overall average maximum lower surface temperature was 92.1°C. The temperature differential between peak upper and lower artifact surface temperatures ranged between 6.0-115.8°C. The average temperature difference for the entire sample was 97.2°C resulting a 49% average temperature differential between peak upper and lower artifact surface temperatures. Figure 2.8 illustrates a typical representation of time/temperature curves associated with the upper and lower surfaces of artifacts during the combustion of fine fuels. In general, heating on the upper surfaces of artifacts was precipitous in which temperatures peaked and declined rapidly. Lower surface temperature curves show that heating on the underside of artifacts was more protracted and less severe compared to that recorded on representative upper surfaces. Overall, however, this differential in heating between artifact surfaces was not sufficient to cause catastrophic failure in any of the artifacts even after the tenth trial. The heat energy generated by combusting fine grassland fuels lacked the intensity and duration to create tensile stresses of the magnitude necessary to induce thermal fracturing of the experimental artifacts The only observable impact of the experiment on the artifacts was the deposition of a condensate tar deposit that initially consisted of a thin light-brown coating after trial 1, and increased in density thereafter as each trial was completed. At the end of 10 trials the artifacts were entirely covered with a thick, dark-brown/black coating of combustive residue. Significant forms of thermal alteration such as thermal spalling, fracturing, or surface cracking were not observed. This experiment further illustrates the limited potential for cool season prescribed fires in grassland fuels to significantly impact common archaeological materials.

Summary

The results of the 2002 experiments at Badlands National Park are similar to those reported for 2001. The average peak surface temperature for the four burn plots included in the 2001 experiment was 195°C. The average peak subsurface temperature at –2cm during this experiment was 26.2°C, an average of only 10.9°C over baseline values. The average maximum surface temperature for the 2002 roadside burn experiment was 157.5°C, and average subsurface temperatures at –2cm and –1cm were 26.2°C and 12.8°C respectively. These peak subsurface values represent minimal increases of 13.6°C and 4.0°C over baseline readings. During the 2002 Pinnacles burn project, peak surface temperatures averaged 120.7°C, and subsurface peak values at –1cm and –2cm averaged 37.1°C and 7.8°C, representing increases of only 11.1-7.7°C over respective baseline values. Overall, average maximum surface temperature across all burn plots was 161.8°C, and average subsurface maximums were 28.6°C at –1cm and 11.4°C at –2cm (average increase of 13.4-7.7°C over baseline). The results of the experiments show that peak surface temperatures within a $2m^2$ burn plot can vary considerably from only 80 °C to nearly 400 °C depending on the combustion consistency of fuels within each quadrant.

Although grassland fuels are homogeneous, there was a wide range of variability in the maximum surface temperature recordings between and within each of the burn plots. Combustion of these fine fuels did not generate sufficient energy release capable of sustaining high temperatures and long residence times at the soil surface. In general, residence times of flaming combustion within 2x2m plots are relatively brief, typically ranging between 1-3 minutes depending on fire behavior. Backing fires will produce longer residence times and the greatest window of heating at the soil surface, generally between 2.5 - 3 minutes. Flanking fires will produce a maximum soil surface-heating window of approximately 1.5 minutes. Head fires produce short window of soil surface heating, generally less than 1 minute. Based on time temperature curves, this generally equates to window of heating above 50°C for approximately 3-6 minutes depending on fire behavior. In general, analysis of the time temperature curves generated during the experiments show that initial heating on the ascending portion of the curve is precipitous in which peak temperatures are achieved within 30-60 seconds. The residence time of peak and near peak temperatures was brief, typically occurring for only 10-20 seconds. The descending portions of the curves were generally more protracted as residual heating is sustained after flaming combustion has ceased. Peak subsurface temperatures, even at –1cm, are negligible generally producing maximum increases of only 13.4-7.7°C at –1cm and –2cm respectively over baseline values.

These data are consistent with the results reported by various by biological science researchers. Archibold et al. (1998) report average maximum surface temperatures of 189°C and 209°C during prescribed burning in northern mixed prairie grasses. Similarly, Bailey and Anderson (1980) reported an average maximum soil surface temperature of 186°C during burning in northern grassland fuels. During burning in annual grasses, Bently and Fenner (1958) recorded maximum soil surface temperatures of 93-120°C. In Kansas tallgrass prairie and Florida sandhill environments, Gibson et al. (1990) report maximum surface temperatures ranging between 19-399°C for the tallgrass biome, and 35-538°C for the sandhill biome. However, the higher temperatures were recorded in association with heavier fuels other than grass. Similarly, Stinson and Wright (1969) report maximum surface temperatures during burning in southern mixed prairie environments ranging between 83-675°C. Again, higher values are associated with fuels other than grasses, and lower values are associated with grassland fuels. These studies also support the observation that residence times in grassland fuels are brief, characterized by rapid heating and cooling intervals.

Concerning the potential negative impact of prescribed burin in mixed grass prairie on archaeological resources, the results of several experiments show that the relatively low surface temperatures and short residence times associated with the combustion of grassland fuels generate minimal thermal alteration of experimental artifacts deposited at the soil surface. The most pervasive form of thermal alteration affecting artifacts was the presence of condensate tar deposit formed during the pyrolysis and combustion of organic fuels. This deposit was generally light brown and color and was limited to the upper surfaces of artifacts. It is likely that over time, these deposits will weather from the surfaces of artifacts since the residue can be removed using water and a pumice soap solution. Some artifact classes with organic components such as bone, and those that are completely organic such as wood did exhibit minimal partial combustion along edges and upper surfaces. No catastrophic forms of thermal alteration such as thermal fracturing, spalling, deformation, or surface cracking were observed during the series of experiments performed at the park during 2001 and 2002. The results of the experiment demonstrate that early-season prescribed burning in mixed grass prairie environments will have a minimal impact on archaeological material located at the soil surface. Archaeological resources located greater than 1cm subsurface will be largely unaffected under the same conditions. These results are consistent with that reported by Brunswig et al. 1995, and that reported by Sayler et al. 1989 for low fuel load burn plots.

MIXED GRASS PRAIRIE / PONDEROSA PINE EXPERIMENTS

Prescribed burning experiments in a mixed grass prairie (multiple species) / Ponderosa pine (*Pinus ponderosa*) environment were conducted at Wind Cave National Park, which is located in southwestern South Dakota, on the southern edge of the Black Hills. Research at the park was performed in mid October 2001 in conjunction with the Bison Flats prescribed burn, and again in May of 2002 during the Highland Creek prescribed burn. Both burn projects were implemented to improve the native vegetation balance at the park. Research at Wind Cave provided a unique opportunity to collect burn plot data in light and moderate fuels simultaneously since vegetation at the park is a mix between grassland and Ponderosa Pine timber stands.

2001 Wind Cave Experiment

Experimental methods employed in 2001 at Wind Cave National Park were similar to those used during the Badland National Park experiments. The experimental artifacts were essentially the same with only minor variations, namely the omission of 2X4 pine scraps and the inclusion of additional mussel shells. In total, four burn plots and approximately 200 experimental artifacts were incorporated into this experiment.

The burn plots consisted of 4 contiguous 2X2m units placed in a location with variable fuels at the transition between grassland and Ponderosa Pine stands. Fuel loads ranged between roughly 4-6 tons per acre (1472-2208 kg/ha) depending on fuel type. Plot 1 contained grassland fuels only. Plot 2 was bisected by a dead/decayed Ponderosa log (15cm dia.), associated branches (<3cm dia.), and grasses. Plot 3 was placed adjacent to the Ponderosa log such that some branches (<3cm dia.) but not the log itself were present, grasses and 2 live Ponderosa sapling (<60cm tall) were also present. Plot 4 contained grasses, 1 live Ponderosa sapling (<60cm tall), and few branches (<3cm dia.).

Results

For safety reason, fire behavior observations were made from a distance making it difficult to gather precise information. However, the flame front developed into a head fire propelled by a 10mph wind and appeared to be moving rapidly (500-1200m per hr) across the burn plots. Flame lengths were estimated at between 1-3m.

The effect of the fire on the experimental artifacts was varied. A general trend can be identified that is directly related to fuel load composition. Artifacts from Plots 1 and 4, placed in light fuels were minimally impacted. Observable effects included slight or no combustive residue deposition and minor charring on the upper surfaces of some bone/shell specimens. Artifacts from Plots 2 and 3, placed near the Ponderosa log and litter, exhibited significant thermal alteration. Bone and shell artifacts were partially combusted and thermally fractured/fissured as well as highly friable during handling post-fire. One pottery sherd exhibited thermal spalling, two lead sinkers were melted, and wooden beads were 75-100% combusted. Overall, each specimen exhibited deeply charred combustive residue deposits that heavily blackened the exposed surfaces of affected artifacts. However, thermal damage of lithic flakes (chert and obsidian) was not observed with the exception of one obsidian flake that exhibited the enhancement of preexisting radial fracture lines. Overall, the results of the artifact analysis show that the heat energy generated by combusting grass fuels (Plots 1-4) was not sufficient to significantly impact most experimental artifacts. This observation is consistent with the results of multiple grassland prescribed experiments conducted at Badlands National Park, and further supports the assertion that cool season prescribed burning in grassland fuels is unlikely to significantly impact most archaeological resources. However, where heavier ground fuels such as dead/decayed logs and associated litter are present (Plots 2-3), the potential for significantly greater heat energy release is probable, and therefore, the potential for significant thermal alteration of archaeological resources is also greater.

Unfortunately, temperature data were not recorded for this experiment due to an overloaded memory in the data recorder (experimenter error). To obtain comparable temperature parameters, the data logger was setup in a separate area that approximated the fuel conditions under which the previous experiment was conducted. No experimental artifacts were included in this experiment, and only temperature data was recorded. Thermocouples 1-2 were placed at the soil surface in grass fuels only. Thermocouple 3 was placed at the soil surface under a dead/decayed Ponderosa log (15cm). Thermocouples 4-5 were placed at the soil surface within the branches (<3cm) and litter associated with the log.

Temperature data for this experiment is summarized in Figure 2.9. As expected, the temperature data were highly variable between fuel load compositions. Maximum temperature in grass fuels reached only 92.0 ˚C, peaking rapidly within 1-1.5 minutes with elevated temperatures being sustained briefly for only 10-20 seconds. Overall, surface heating in grass fuels was sustained above 50°C for approximately 7 minutes. Maximum surface temperatures in branch/grass fuels reached apex levels over a more protracted duration of approximately 10 minutes in which maximum values for the two thermocouples were recorded at 261.5°C and 471.0˚C. Here surface temperatures in excess of 200°C were sustained for approximately 8 minutes and 20 minutes for each respective thermocouple. Maximum surface temperatures recorded beneath the log were the greatest, reaching the 615.1˚C mark. Here temperatures greater than 500°C were sustained for approximately 22 minutes, followed by a gradual reduction in temperature in which values remained in the 200˚C range for over 2 hours. These data illustrate the significant temperature differential generated by fuels of various composition within a small spatial unit, and further support the assertion that fuel load and residence time are critical variable affecting the potential for significant thermal alteration of archaeological resources. While these temperature data are not directly correlated with observed thermal alteration of experimental artifacts, they can be used as an analog by which to assess the thermal alteration of experimental artifacts observed in Plot 1-4 during the initial experiment.

2002 Wind Cave Experiment

During the 2002 prescribed burn project at Wind Cave, one 2x2m burn plot divided into four quadrants containing approximately 50 experimental artifacts was placed in a wooded drainage. One elk antler and one deer mandible found near the burn unit were also included in the experiment. The burn plot was placed on a 10-15% slope with a North aspect towards the upper (eastern) portion of the drainage. Fuels consisted of Ponderosa Pine duff and litter (two 2m x 3-4cm dia. branches, 2cm of loose pine needles, and 2-3cm duff accumulation). Mixed grass prairie fuels in the vicinity were heavily grazed and unlikely to carry sufficient flaming combustion, and therefore, were not included in the experiment. The burn plot was intentionally positioned in the heaviest fuels available within the burn area to observe the maximum surface temperatures that could be generated during the prescribed burn. Thermocouples 1-4 were placed at the soil surface (beneath the duff) in each of the four quadrants. Thermocouple 5 was placed at –1cm beneath the soil surface, and thermocouple 6 was placed –2m subsurface with in quadrant 1.

Results

Fire behavior was observed at a distance as the flames backed down into the drainage from three sides. Flame lengths were observed to be between 20-30cm, and burned across the burn blot within approximately 5 minutes. Glowing and flaming combustion continued for approximately another 10 minutes, and smoldered for an additional hour.

Graphical summarizations of the time/temperature data for the experiment are provided in Figure 2.10. Maximum surface temperatures ranged between 286.2-513.5°C and reached apex levels within approximately 10 minutes within each quadrant. However, the temperature gradient within each quadrant was varied. Quadrant 2 sustained heating >400°C for approximately 16 minutes, quadrant 3 experienced temperatures >300°C for approximately 9 minutes, quadrant 4 sustained heating >200°C for 22 minutes, and temperatures >200°C within quadrant 1 were only sustained for approximately 9 minutes. This variability is likely due to differential fuel combustion within the burn plot. Subsurface temperatures at –1cm increased from 4.8-74.7 °C, and temperatures at –2cm increased from 8.0-64.2 °C; both over a period of approximately 30 minutes. Overall, the greatest proportion of surface and subsurface heating occurred over a period of 25 minutes as temperatures peaked and fell gradually to below 50 °C after approximately 45 minutes. These data suggest that duff and litter fuels can generate sustained surface heating in the 200-400°C range for approximately 10-20 minutes.

Post-fire analysis of the experimental artifacts shows that all specimens exhibited heavily blackened combustive residue deposits on exposed surfaces. Significant thermal alteration was pervasive for bone, antler, and shell specimens, which exhibited intensive thermal fracturing/fissuring, heavy charring/partial combustion, and a considerably increase in friability. Wooden beads from each quadrant sustained combustion rates of 75-100%. In addition, one pottery sherd from quadrant 3 exhibited thermal spalling and fracturing, and a lead sinker form the same sample sustained complete deformation due to melting. One glass fragment (bottle glass) from the quadrant 4 sample exhibited thermal spalling. None of the lithic specimens from the overall sample exhibited thermal fracturing. Overall, the impact of the burn on the experimental artifact was most pronounced and consistent for organic specimens. This experiment illustrates the potential for combusting Ponderosa pine litter and duff fuels to generate sufficient heat energy to significantly alter some types of archaeological resources deposited at the mineral soil surface. Thermal alteration of subsurface archaeological deposits > -2cm is not probable. The results of this experiment are similar to those observed during the previous experiment conducted during the Bison Flats prescribed burn at Wind Cave in October of 2001.

Summary

The results of the two prescribed burn experiments conducted at Wind Cave National Park suggest that the potential for significant thermal alteration of archeological resources is largely dependent on fuel composition, burn duration, and artifact class. The first experiment illustrated the significant differential in heat energy generated by grass fuels and log/litter fuels. Combustion of grass fuels produced limited peak temperatures and brief residence times, which in turn, had a minimal impact on experiment artifacts (combustive residue deposition). Conversely, the combustion of litter and log fuels during both experiments at the park generated peak temperatures of >600°C for log fuels and >400°C for litter fuels. In addition, temperatures in the 200-400°C in litter fuels can be sustained for up to 20 minutes; and log fuels can sustain temperatures >500°C for the same duration. The impact of these combusting fuels on surface experimental artifacts was most prominent for organic specimens such as bone, shell, and wood. These materials exhibited heavy charring/combustion, thermal fractures/fissures, and a pronounced increased in post-fire friability. In addition, thermal spalling/fracturing of pottery sherds and glass, and melting of lead specimens was observed within in some burn plot quadrants, particularly those experiencing sustained heating. However, significant thermal alteration of subsurface archaeological resources in the mixed grass prairie / Ponderosa pine environment is unlikely to occur regardless of fuel load, unless combustion of tree root systems occurs.

MIXED CONIFER FOREST EXPERIMENTS

Fire effects experimentation was conducted in a mixed conifer environment within the Pike National Forest along the Colorado Front Range during September 2001 in conjunction with the Pohemus Gulch prescribed burn project, and during the Schoonover wildland fire in May of 2002. Research within the forest provided an opportunity to collect burn plot data under moderate to heavy fuel conditions. The dominant vegetative community within the study area consists of a mixed Douglas Fir (*Pseudotsuga menziesii*) and Ponderosa Pine (*Pinus ponderosa*) forest accompanied by an understory of various grasses and forbs. Fuel load was estimated in the 8-10 ton per acre range (2944-3680 kg/ha).

2001 Pike National Forest Experiment

Experimental methods implemented during this project were similar to those discussed for previous experiments. One 2X2m burn plot was setup with approximately 50 experimental artifacts (similar to artifacts used in previous experiments). The plot was orientated such that a dead/decayed conifer log (30cm dia.) and associated branches bisected the unit. Other fuels included a 5-10cm thick duff/litter accumulation, minimal grasses, and forbs. Thermocouples 1-4 were placed within in each respective $1m^2$ quadrant at the mineral soil surface beneath the duff/litter accumulation. Thermocouple 5 was placed –5cm subsurface beneath the log, and thermocouple 6 was placed –10cm subsurface underneath the log. Artifacts positioned in quadrants 1 and 3 were placed at the mineral soil surface (beneath the duff) in close association (~5-10cm) with the log. Artifacts associated with quadrant 2 were placed at the soil surface beneath a 5cm duff accumulation not in association with the log (~70cm NW of log). Quadrant 4 artifacts were positioned at the soil surface beneath an 8cm accumulation of duff, and approximately 30 cm N of the log. The variable fuel composition within each quadrant was structured to assess the potential for differential soil surface heating and artifact thermal alteration.

Results

Fire behavior observations show that a head fire, pushed by 5-8 mph wind velocity, generated 1-3m flame lengths, and passed over the burn plot within approximately 5 minutes. Flaming and glowing combustion continued in lighter fuels for approximately 15 minutes; however, the log and other larger fuels sustained flaming and glowing combustion for over 3 hours.

Maximum surface temperatures within quadrants 1 and 3 (close proximity to log) reached peak values of 350.9˚C and 326.0˚C gradually over a prolonged period of approximately 4-6 hours. Surface temperatures within these quadrants also declined slowly, whereby temperatures >100°C were sustained for 6.6-7.5 hours. Peak surface temperatures within quadrant 2 (light fuels) reached 397˚C rapidly within 8 minutes, then began to decline quickly with temperatures >100°C being sustained for only 45 minutes. Surface heating within quadrant 4 (light fuel) reached a maximum value of 188.7˚C over a period of approximately 45 minutes. Surface temperatures here were sustained at >100°C for approximately 1 hour. Duff combustion within quadrant 2 was more extensive than within quadrant 4, possibly accounting for the differential in maximum temperature and duration of heating observed between the two quadrants. This suggests that duff may mitigate the soil surface heating in instances where duff is not heavily combusted. The maximum subsurface temperature at –5cm beneath the log was 139.0˚C, which was recorded over 4 hours after flaming combustion was initiated within the plot. Similarly, the maximum temperature at –10cm of 107.5˚C, was recorded over 5 hours post ignition as the log continued to combust over an extended period. Time/temperature data for the experiment are presented graphically in Figure 2.11. These data illustrate the variability in surface heating recorded within the burn plot. The time/temperature curves associated with heavy fuel (log) are smooth and protracted, whereas those associated with lighter fuels (duff) show precipitous temperature gradients. Subsurface curves are smooth and protracted suggesting uniform heating below the surface of the log.

The impact of the fire on the experimental artifacts was proportional to their proximity to the heavier fuel load of the log. Artifacts in quadrants 2 and 4 (light fuels) exhibited heavy combustive residue deposits on the upper surfaces of all specimens. Bone and shell specimens from these quadrants also exhibited moderate charring and partial combustion on upper surfaces. No thermal fracturing, spalling, or deformation was observed. Within quadrants 1 and 3, bone and shell exhibited heavy charring and combustion, as well as thermal fracturing/fissuring and increased friability. In addition, lead was melted, wooden beads were partially combusted, and obsidian artifacts exhibited enhanced radial fracture lines.

The results of the post-fire artifact analysis illustrate the direct relationship between the potential impact of prescribed fire on surface archaeological materials and fuel load composition. Artifacts positioned near the log were subjected to temperatures in excess of 300˚C for over 1 hour in quadrant 3 and three hours in quadrant 1. Subsequently these artifacts were more heavily impacted by the release of radiant heat energy from the heavier fuel compared to artifacts burned in duff where temperatures peaked and fell more rapidly. Subsurface temperatures –5cm and –10cm beneath the log were elevated over 100˚C for 1-2 hours; however, it is unlikely that archaeological materials deposited at these depths would have been significantly impacted since peak temperatures were low and heating was uniform and prolonged over a period of several hours. Overall, the results of the experiment further support the assertion that heavier fuels equate to greater potential heat energy output during combustion, which in turn, increases the potential for significant thermal alteration of archaeological resources.

Log Burning Experiment

In addition to the burn plot experiment conducted during the 2001 prescribed burn, a log burning experiment consisting of four trials was also performed. Each of the four trials consisted of a 1x1m burn unit positioned over a downed/dead conifer log and associated surface litter and duff. Temperature and time data were recorded using the data logger and 6 thermocouple leads placed in a linear orientation beneath logs and associated litter/duff at the contact with the mineral soil. Lithic artifacts were also placed at the soil surface in association with the thermocouples. The lithics were modernly replicated flaking debris representing four selected lithic material types common in the archaeological record (obsidian n=10, porcelanite n=8, phosphoria n=6, pink bioclastic chert n=8, N=32). Prior to burning each specimen was measured, weighed, and assigned a Munsell color value. Post-burn, each specimen was analyzed for evidence of thermal alteration, weighed and assigned a Munsell color value. The purpose of this experiment was to collect additional temperature data associated with the combustion of conifer log fuels, and to assess the impact of the heat energy released during combustion on a range of lithic material types.

Results

Fuels in Trial 1 consisted of a 15cm diameter conifer log that extended across the unit and a thin duff accumulation, measuring approximately 1cm in depth. Fuel combustion during burning was uniform and complete. Maximum surface temperatures beneath the log ranged widely between 269.0-878.9°C. Temperatures peaked within 10-35 minutes and tapered off to <100°C over a period of 4 hours. Thermal alteration of lithic specimens consisted of a combustive residue deposit, resulting in a blackened discoloration on the upper surfaces of all specimens. In addition to the combustive residue deposits, the chert and phosphoria flakes also exhibited an overall color change to a darker Munsell value suggesting that heating had altered the mineralogy of each specimen. More importantly, one of the chert flakes was thermally fractured into 3 pieces during this experiment. The peak temperature associated with this specimen was 348.9°C, which was recorded approximately 30 minutes after initiation of flaming combustion. The obsidian flakes exhibited a metallic sheen and the enhancement of radial fracture lines on upper surfaces. The peak temperature associated with these specimens was 276.6°C, recorded within 30 minutes of initial combustion. Porcelinite flakes exhibited no structural damage during the trial.

Trial 2 fuels consisted of one 10cm diameter log extending the across the unit, and a 3cm deep duff accumulation. Fuel combustion was uniform and complete during the trial. Maximum surface temperatures ranged between 366.4-602.0˚C. Temperatures peaked within 20-40 minutes and declined slowly to <100°C over an extended period of approximately 4 hours. Thermal alteration of the experimental lithics was similar to those discussed for trial 1. One of the chert flakes was thermally fractured into 2 pieces, and exhibited the same shift in overall color as seen in trial 1. The maximum temperature associated with this specimen was 424.1°C. In addition, one of the phosphoria flakes exhibited a classic potlid fracture (28.33mm in dia.) on its upper surface. The maximum temperature associated with this specimen was 490.6°C. The obsidian specimens exhibited a metallic sheen and enhanced radial fracture lines on upper surfaces. The maximum temperature associated with these specimens was 432.5°C. All specimens were discolored by combustive residue deposition on upper surfaces, and the chert and phosphoria specimens exhibited a shift to a darker hue suggestive of mineral alteration.

Fuels in Trial 3 consisted of a conifer log (10cm in diameter) that extended across the burn unit, and a duff accumulation measuring approximately 3cm in thickness. Fuel combustion during the trial was uniform and complete. Maximum surface temperatures ranged between 319.7-540.8˚C. Temperatures peaked rapidly within 15-30 minutes followed by a gradual reduction in temperature in which temperatures >100°C were sustained for over 4 hours. Thermal alteration of the experimental lithics was consistent with that reported for the previous trials. Combustive residue deposits were observed on the upper surfaces of all specimens, and chert and phosphoria specimens exhibited color alterations suggestive of mineral oxidation. The obsidian specimens exhibited enhanced radial fracture lines as well as a metallic sheen on upper surfaces. The peak temperature associated with these specimens was 450.7°C. In addition, one of the phosphoria flakes exhibited a small (3.49mm) potlid fracture. The other phosphoria flake exhibited fine crazing on the upper surface. The peak temperature associated with these specimens was 362.8°C.

The burn unit in trial 4 included two logs extended across the 1x1m unit, each of which measured approximately 30cm in diameter. The duff accumulation within the unit was approximately 7 cm thick. Compared to the previous experiments, the fuels in this experiment were the heaviest. Fuel combustion during the trial was uniform and complete. Maximum surface temperatures ranged from 403.4˚C to 831.4˚C, peaking within a variable period of 15-60 minutes. Heating within the unit was erratic due to natural movement of one of the logs during combustion. Thermal alteration of the experimental lithics was similar to those reported previously. All specimens exhibited combustive residue deposition on upper surfaces. Obsidian specimens exhibited enhanced radial fracture lines as well as an alteration of the upper surfaces in which the original color was altered to a metallic sheen. The maximum temperature associated with these specimens was 567.7°C. Interestingly, although surface heating was considerable during the trial, no chert of phosphoria specimens sustained thermal fractures. There was, however, one exception in which one porcelinite flake was thermally fractured into 2 pieces. The maximum temperature associated with this specimen was 831.4°C.

Combined time and temperature data for all 4 experiments are summarized in Figure 2.12. The uppermost peak surface temperature recorded for trials 1-4 ranged between 878.9-503.2˚C. During each trial, surface temperatures in excess of 200˚C were maintained for up to 3 hours. In general, temperatures reached apex levels within a broad period between 10-60 minutes; however, the decline in temperature from peak levels was typically more gradual in which temperatures >100°C were sustained for approximately 4 hours. Overall, a wide range of maximum temperatures, and variable rates of temperature increase and decrease were recorded during the experiment. This variability is likely the result of differential rates of glowing and flaming combustion and oxygen availability that occurred while the log was being consumed. These data suggest that surface heating beneath combusting logs is characterized by relatively rapid temperature ascent to peak levels, prolonged periods of sustained high temperature, and protracted declines in temperature on the descending side of maximum values.

Thermal alteration of the experimental lithics from each experiment can be summarized as follows:

Obsidian: Blackening/carbonization, chrome-like gloss, and linear crazing occurring on the side-up surfaces, observed in 100% of the sample (N=10). Maximum temperatures associated with these form of thermal alteration ranged between 276.6-567.7°C for an average temperature of 431.8°C.

Chert: Blackening/carbonization as well as an overall color change from 10R 7/3 to 10R 6/3, a darker value for the 10R hue, observed in 100% of the sample (N=8). Extensive fracturing resulting in the flake breaking into multiple pieces, observed in 25% of the sample. Maximum temperatures associated with fractured specimens ranged between 348.9-424.1°C. *Phosphoria*: Blackening/carbonization, and an overall color change from 10R 3/4 to 10R 3/2, a darker chroma value, observed in 100% of the sample (N=6). Potlid fracturing was observed in 30% of the sample, and crazing was observed in 16% of the sample. Maximum temperatures associated with thermal fracturing and crazing ranged between 362.8-490.6°C. *Porcelanite*: Blackening/carbonization with no overall color shift, observed in 100% of the sample. Fracturing was observed in 12% of the sample (N=8). The maximum temperature associated with the thermally fractured specimen was 831.4°C.

These data suggest the levels of heat energy released during the combustion of dead/decayed conifer logs during prescribed burns is sufficient to induce significant thermal alteration of selected lithic material types included in the experiment, given that specimens are deposited directly beneath logs. Significant forms of thermal alteration observed included thermal fracturing and mineral oxidation of pink bioclastic chert, potlid fracturing and crazing of phosphoria, enhanced radial fracture line propagation and surface alteration (metallic sheen) of obsidian, and thermal fracture of porcelinite under extreme temperature gradient.

2002 Pike National Forest Experiment

Fire impact experimentation was resumed within the Pike National Forest during the Schoonover wildland fire that burned a portion of the forest near Deckers, Colorado in May of 2002. The experiment was designed to be simple and expedient given the volatile nature of wildland fire. However, by the time a suitable location was selected for the experiment the fire was burning at a rather low intensity similar to prescribed fire conditons.

The experiment consisted of a 1x1m burn plot placed over a 20cm diameter conifer log that was associated with a 2-3cm duff accumulation (mostly loose pine needle).

Experimental artifacts consisted of 2 deer (*Odocoileus sp.)* metatarsals, 2 black-on-white pottery sherds, 2 Hartville Uplift chert nodules, 2 obsidian secondary flakes, and 2 Pecos chert primary flakes. Descriptive artifact information was recorded pre-fire and post-fire. Temperature measurement was achieved using two methods; the primary system used during the previous experiments, and a secondary system that was being field tested for the first time (see methods section). The secondary system was used to gather temperature data on the upper and lower surfaces of three artifacts (bone, sherd, and chert core) to assess the temperature differential between artifact surfaces during burning since thermal fracturing of brittle materials is linked to differential thermal stress induced by disproportionate heating. All artifacts were placed in close association (0-5cm) of the log in a linear orientation. The primary temperature recording system was used to gather soil surface temperature data at several points within the plot. Thermocouples 1-2 were placed beneath the log, 3-4 were placed underneath the duff accumulation, and 5-6 were placed –2cm and –5cm subsurface beneath the log.

<u>Results</u>

Fire behavior observations recorded during combustion show that the plot was burned during a slow moving low-intensity backing fire that produced flame lengths of approximately 20-30cm. Time/temperature data for soil surface measurements are summarized graphically in Figure 2.13. The figure clearly illustrates the considerable differences in soil surface heating associated with the log, duff only, and subsurface beneath the log. Temperatures directly beneath the log reached peak values of 632.6°C and 739.8°C. The temperature gradient was characterized by a rapid ascent to apex levels within 5-7 minutes with temperatures >500°C being sustained for 7-12 minutes and temperatures >300°C being sustained for 20-40 minutes. Thermocouples associated with duff fuels only reached peak levels of 223.9-259.3°C rapidly within approximately 3 minutes. Temperatures then declined rapidly to <100°C within approximately 5-8 minutes. Subsurface temperatures beneath the log at –2cm reached a peak value of 226.0°C, and 105.7°C at the –5m level. Here the temperature gradient was smooth and protracted in which peak values were recorded after approximately 1 hour, and heating >50°C was sustained for approximately 3 hours. These data illustrated the variability in soil surface heating on the floor of a mixed conifer forest during a low-intensity fire. Heating is extreme where large fuels are combusted and minimal where only duff is consumed.

The result of the artifact heating component of the experiment show that peak temperatures on the upper surfaces of selected artifacts ranged between 753.5-583.4°C and maximum values on the lower surfaces of artifacts were recorded in the 515.1-436.8°C range. Time/temperature data are provided in graphical form in Figure 2.14. Upper surface peak temperatures were achieved rapidly within 2-10 minutes and lower surface maxima were recorded within approximately 10-20 minutes. Upper surface heating was erratic and precipitous, while heating on the lower surfaces of artifacts was more uniform and protracted. Overall, artifacts experienced temperatures >300°C for a prolonged period of 30-60 minutes.

Thermal alteration of experimental artifacts was significant. All specimens exhibited a heavily charred combustive residue deposit on exposed surfaces. Bone specimens were heavily charred, combusted, fractured/fissured, and very friable. Peak upper and lower surface temperatures associated with the bone specimen with attached thermocouples were 735.5°C and 463.4°C respectively. Peak temperatures associated with the chert nodule were 682.5°C for the upper surface and 436.8°C for the lower surface. This specimen exhibited extreme thermal fracturing that reduced the specimen to many small fragments (>50), and sustained mineral oxidation (probably limonite to hematite) that altered the original yellow-brown color to red. The chert primary flake also exhibited thermal fractures, but to a lesser extent than the nodule, as well as a shift in color to dark red suggestive of mineral oxidation. The upper surface maximum temperature recorded for the pottery sherd was 583.4°C, and the peak lower surface value was 515.1°C. No thermal fracturing or spalling was observed for either of the pottery sherds, only a highly blackened combustive residue deposit on the upper surface of the sherds was noted. This deposit did, however, obscure the design characteristics of the sherds. Obsidian artifacts exhibited enhanced radial fracture lines and a metallic sheen on upper surfaces, but evidence of thermal fracturing was not observed. No temperature data were recorded for these specimens.

Overall, the results of this experiment illustrate the variability in surface heating during low-intensity wildland fire in a mixed conifer environment. Soil surface temperatures were highly variable depending on fuel load composition. Light duff fuels generated low peak temperatures (223.9-259.3°C) characterized by brief residence time in which temperature peaked within 3 minutes and fell off sharply within 5-8 minutes. Conversely, peak soil surface temperature beneath a combusting log ranged between 623.56-739.8°C and were sustained at >300°C for 20-40 minutes. Most experimental artifacts associated with the log experienced significant degrees of thermal alteration, particularly bone and chert specimens. However, pottery sherds were not affected structurally. Upper surface temperatures recorded on selected artifact were consistent with soil surface temperatures recorded beneath the log. In sum, the combined data illustrate the important relationship between fuel load as it affects the potential for significant thermal alteration of archaeological materials during wildland and prescribed fire.

Summary

In sum, the experiments performed in conjunction with prescribed and low-intensity wildland fires in mixed conifer fuels suggest that the impact of heat energy released during combustion on archaeological materials is variable and largely dependent on artifact class and the association of artifacts relative to large fuels. Decayed logs on the forest floor can generate soil surface temperatures in the 400-800°C. Artifacts associated with these fuels generally exhibit significant thermal alteration such as thermal fracturing among lithics and heavy charring, combustion, and fracturing of bone and shell specimens. The results of several trials in which combusting logs were present show that thermal fracturing of chert and phosphoria artifacts is initiated when soil surface temperatures reach the 350-490°C range, and sustain pronounced fracturing when the upper surfaces of artifacts reach the 500-680°C range. Thermal fracturing of chert artifacts is most prominent for larger specimens such as nodules (cores, etc.) where the potential for disproportionate heating within the material is greater due to larger body mass. Mineral oxidation within Pecos and Hartville Uplift cherts was also observed in conjunction with thermal fracturing. Obsidian secondary flakes exhibited enhanced radial fracture lines and a metallic sheen on upper surfaces in association with temperatures in the 400°C range. Bone, shell, wooden, and lead specimens were observed to exhibit significant thermal alteration when burned in association with heavy fuels. Pottery sherds, however, did not exhibit thermal spalling or fracturing. In instance where only duff fuels are present, the probability of marked thermal damage of archaeological materials is not as significant due to reduced fuel load. These results further illustrate the direct relationship between significant thermal alteration of archaeological materials and combustion of heavy ground fuels during prescribed burns and wildland fire. The most effective way to mitigate potential thermal damage of archeological resources located in conifer environments is to remove hazardous fuels from know archaeological sites prior to the implementation of prescribed burn plans or where wildland fire highly probable.

RIPARIAN ZONE AND SAGEBRUSH COMMUNITY EXPERIMENTS

Prescribed burn experiments were conducted at Grand Teton National Park in conjunction with the Jackson Lake Lodge prescribed burn during May of 2002, and again in September of 2002 during the Kelly prescribed burn. The Jackson Lake burn was conducted in a riparian environment, and the Kelly burn occurred within a sagebrush community. Each of the burn projects provided a unique opportunity to expand the archaeological field-based experimentation to different fuel models.

Jackson Lake Lodge Prescribed Burn

Fuels in the burn area consisted predominantly of various willow species and associated grasses in a low-lying riparian type environment. Consequently, the soil surface contained high levels of moisture content. The experiment included two 2x2m burn plots in which experimental artifacts were burned, two 1x1m burn plots in which upper and lower surface temperatures of experimental artifacts were recorded, and two additional trials where only surface temperatures beneath a large willow and small sagebrush were recorded.

The first component of the experiment consisted of one 2x2m burn plot (Plot 1) that encompassed a small booth willow (*Salix boothii)* (1.5 x 2m) and associated grasses, largely beaked sedge (*Carex rostrata*). Experimental artifacts (N=14), representing the range of artifact classes (i.e., bone, shell, chert, obsidian, glass, and metals) included in previous experiments were placed in quadrant 1 only. Temperature data were recorded using the primary OM 3000 system. Thermocouples were placed at the soil surface within each of the four quadrants comprising the 2x2m spatial unit. Thermocouple 5 was placed –1cm subsurface, and thermocouple 6 was placed –2cm subsurface. Two additional 1x1m burn plots were also included in the experiment. Here the secondary temperature recording method was used to assess upper and lower surface artifact temperatures during the burn. Each plot (plots 2-3) contained three artifacts (2 black-on-white pottery sherds, 2 obsidian secondary flakes, 2 Hartville chert nodules). Temperature data within each plot were recorded using one data logger and six thermocouples leads that were attached to the upper and lower surfaces of the experimental artifacts. Fuels within each of the 1x1m burn plots consisted of one small wolf willow (*Salix geyeri*) (1 x 1.5m) and associated grasses, primarily beaked sedge (*Carex rostrata*). The goal of the experiment was to record soil surface and subsurface temperatures as well as the differential in temperatures between the upper and lower surfaces of artifacts during the burn; and to correlate these data to potential thermal alteration of the experimental artifacts observed post-burn.

Fire behavior observations near each of the 3 burn plots (encompassed within a $10m^2$ area) show that burning within the units was accomplished by a backing fire, which generated flame lengths of approximately 30-50cm and a rate of spread of approximately 1m per 2.5 minutes. The fire consumed the upper organics on the soil surface only, leaving the willows partially scorched to approximately 45cm from the base. The duff layer was not combusted and the O horizon remained cool and moist.

Time/temperature data for Plot 1 are summarized in Figure 2.15. The results from plot 1 show maximum surface temperatures ranging only between 95.9-140.4 °C. Temperature reached apex levels rapidly within 1.5 minutes, and only sustained heating >50°C for approximately 9 minutes. Peak temperatures were maintained over a period of approximately 30 seconds. Subsurface temperatures at –1cm rose only slightly from 4.3-8.0 °C, and temperatures at –2cm were also elevated only slightly from 4.0-7.0 °C.

Time/temperature curves for the subsurface thermocouples were very protracted, indicating very slow heating.

Time/temperature data for upper and lower artifacts surfaces from Plot 2 are summarized in Figure 2.16. These data show that heating on the upper surfaces of artifacts was precipitous and erratic, while heating on the lower surfaces was minimal and protracted. Peak temperatures recorded on upper artifacts surfaces reached highly variable peak temperatures of 265.7-28.0 °C. Heating on the upper surfaces of artifacts was rapid, reaching peak levels within approximately 30 seconds. Elevated temperature were sustained only briefly for a few seconds, then temperature fell off to <50°C within 4-10 minutes. These data are consistent with soil surface heating observed in Plot 1. Peak temperatures recorded on lower artifact surfaces varied between minimally between 28.0-59.3 °C.

Time/temperature data for artifact surfaces from Plot 3 are provided in Figure 2.17. Within this burn plot, peak temperatures on the upper surfaces of artifacts ranged moderately between 244.5-355.0 °C. Peak values were reached within approximately 30 seconds and sustained very briefly. However, overall heating on the upper surfaces of artifacts was more significant within Plots 3 with temperatures of >100°C being sustained for 5-15 minutes. Heating recorded from lower artifact surfaces attained maximum temperatures ranging from 47.8-215.2 °C. The 215.2°C is anomalous, and is likely the result of a thermocouple becoming dislodged from the under-side of the artifact during burning. Overall, lower surface heating was slow and uniform, and upper surface heating was rapid and irregular.

The impact of the fire on all of the experimental artifacts from each of the three burn plots was minimal. Post-burn analysis of the artifacts showed that the only observable form of thermal alteration present was a light deposit of golden-brown combustive residue on the upper surfaces of artifacts, similar to that observed during the mixed grass prairie experiments. Bone and shell specimens were not charred or partial combusted, only slightly discolored. No significant forms of thermal alteration of experimental artifacts such as thermal spalling, cracking, or fracturing were observed. The results of the artifact analysis are consistent with the temperature data generated during the experiment. The heat energy generated during combustion was characterized by rapid heating in which peak values were sustained for approximately 30 seconds, followed by a rapid decline in temperature within a brief period of 5-15 minutes. The fuels within each plot did not generate the temperature gradient necessary to initiate thermal fracturing, charring, or other types of thermal damage within the artifact sample.

During the experiment it became apparent that combustion of small willow and fine grasses during the prescribed burn would not generate the heat energy necessary to significantly impact experimental artifacts. As a result, an additional 1x1m burn plot was established in heavier fuels. Burn Plot 4 was placed at the base of a large willow (3.5 x 3.5m, *Salix geyeri* ?) that was also associated with an accumulation of small dead fuels. Fourteen experimental artifacts (various classes, bone, lithic, metal, glass, etc.) were placed at the soil surface next to the base of the willow. Thermocouple 6 was placed at the soil surface in association with the artifacts. The remaining thermocouples were placed at 25cm intervals in a linear orientation radiating outward from the base of the willow (as in experiment 2). The purpose of this trial was to establish the temperature ranges generated at the base of a large willow, and at intervals radiating outwards beneath its understory.

Fire behavior observation show that the willow ignited and torched into the crown rapidly, and flaming combustion was observed for approximately 17 minutes. Glowing and smoldering combustion was observed for an additional 18 minutes, and the willow was observed to be approximately 80-85% combusted at the end of the combustion phase.

Time/temperature data associated with Plot 4 are summarized in Figure 2.18. The maximum surface temperature recorded by the thermocouple associated with the artifacts reached 497.8 °C. Here temperatures peaked within 9 minutes and were sustained at near peak levels for approximately 30-60 seconds. Temperatures in the range of >300°C were sustained for ~10 minutes, >200°C were sustained for ~20 minutes and >100°C were maintained for ~30 minutes. The remaining 5 thermocouples recorded maximum surface temperatures ranging between 52.5-320.2 °C. Peak temperatures diminished in magnitude with each 25cm interval radiating from the base of the willow. However, heating was uniform across each thermocouple with each time/temperature curve following a similar contour. Overall, surface temperatures peaked and fell gradually to below 50 °C over a period of approximately 50 minutes.

Post-burn analysis of experimental artifacts showed the presence of a moderate to heavy combustive residue deposit present on the exposed surfaces of all specimens. The bottle glass specimen exhibited a thermal fracture that split the specimen into halves. Bone specimens exhibited charring and partial combustion on upper surfaces as well as the propagation of surface cracks. Thermal fracturing of lithic materials was not observed. This trial illustrates that the residence time and maximum temperatures associated with a large, heavily combusted willow are sufficient to significantly impact some types of archaeological materials, particularly organics and glass. However, these materials were placed directly at the base of the willow. Materials deposited subsurface or at distances greater than 25cm from the base are unlikely to be significantly impacted.

Two additional trials were conducted during the Jackson Lake project on an opportunistic basis with the purpose of collecting data on surface temperature only. The first trial consisted of placing 6 thermocouple leads around the base of a moderately large willow

(3 x 3m, species?). Thermocouples 1-2 were placed at the soil surface next the base of the willow (the area at which it emerges from the soil surface). Thermocouples 3-4, and 6 were place 25cm away form the willow base, but beneath the radial extent of its branches. Thermocouple 5 was placed 50cm from the base under the branching willow.

The willow was burned via a backing fire with flames reaching into is crown, however, burning was sporadic and combustion of the willow was less than 50%. The maximum surface temperatures for thermocouples positioned near the base of the willow ranged between 257.0-289.3 °C. The maximum surface temperatures for thermocouples positioned 25cm from the base ranged between 126.9-84.4 °C. The thermocouple placed 50cm away from the base recorded a maximum surface temperature of only 26.5 °C. Maximum temperatures were maintained for approximately 2.5 minutes with temperatures tapering out to below 50 °C within approximately 8.5 minutes. Maximum surface temperatures next to the willow base were significantly higher than those 25cm away from the base. Higher concentrations of live and dead fuels were observed near the base of the willow prior to ignition. These fuels may be heavy enough to sustain critical temperatures in the range that can significantly impact archaeological materials deposited at the soil surface.

The following trial was similar to the previous with the exception that the source of fuel was a small sagebrush (*Artemisia tridentada*, 1.5 x 1.5m). Thermocouples 1-2 were placed at the soil surface adjacent to the trunk of the sagebrush. Thermocouple 3 was placed at the soil surface 15cm away from the base beneath the radiating branches of the sagebrush. Thermocouples 4-5 were placed 25cm from the base, and 6 was positioned 50cm from the base. During the experiment thermocouple 1 popped out of position at the soil surface and was suspended at approximately 5cm above the soil surface. The maximum temperature recorded for this thermocouple was an anomalous 701.2 °C. The maximum surface temperature for thermocouple 2 was 212.8 °C. The maximum surface temperatures recorded by thermocouple 3-6 ranged between 336.8-163.0 °C. Temperatures peaked and fell gradually to below 50 °C over a period of 20 minutes. Maximum temperatures for thermocouples 2-6 were fairly consistent regardless of their position relative the trunk of the sagebrush.

<u>Summary</u>

The result of the Jackson Lake experiment demonstrate that soil surface temperatures generated by a prescribed fire in a riparian zone dominated by willow and sedges can vary significantly depending on fire behavior, the size of fuels, and extent of combustion of fuels. The fuels ignited in Plot 1 were characterized by small willows and grasses which, when ignited, only generated maximum surface temperatures between 95.9-140.4 °C. These temperatures are not sufficient to generate radiant heat energy capable of significantly affecting most archaeological materials (with the exception of wood and other organics). Similarly, heating of artifact surfaces within the same fuel composition produced peak temperatures of up to 355.0°C on the upper surfaces of artifacts, and nearly 60°C on lower surfaces (excluding anomalous value). This is a significant temperature differential; however the severity and duration the heat energy generated by fine fuels was not sufficient to initiate stress within artifacts capable of producing thermal fracture. However, the results from Plot 4 illustrate that temperatures generated at the soil surface by a large willow produce maximum temperatures of 497.8 °C (at the base), and have a more sustained residence time compared to lighter fuels. Enough radiant heat energy is transmitted to the soil surface by these larger fuels to significantly impact some archaeological materials, if the materials are deposited near the base of large willows. Overall, the impact of spring prescribed burning in a riparian zone on archaeological materials is mitigated by high soil and fuel moisture content.

Archaeological materials will be significantly impacted only if sufficient combustion of large fuels occurs in tandem with closely associated surface archaeological materials. However, it is highly unlikely that subsurface archaeological deposits will be adversely affected during prescribed burns in riparian environments.

Kelly Prescribed Burn

Additional fieldwork was conducted at Grand Teton National Park in junction with the Kelly Prescribed Burn on September 28, 2002. This prescribed burn provided much needed data on effects of burning sagebrush fuels on archaeological materials as well as time and temperature curves associated with these fuels. The experiment consisted of two distinct trials using a research design similar to that used during previous prescribed burn experiments.

Plot 1 consisted of one 2x2m burn unit situated within a group of 9 small to medium sized (1m x .75m, 7cm dia. trunk) *Artemisia tridentata* and associated grasses. Sagebrush canopies were relatively thin, and dead under-story accumulations were sparse. The 2x2m plot was divided into four 1x1m quadrants, each containing one or two sagebrush and associated grasses. Thermocouples 1-4 were placed at the soil surface approximately 10cm from the base of a sagebrush in each of the four quadrants. Experimental artifacts were place in each quadrant within a 20cm radius of each respective thermocouple lead. Experimental artifacts were the same for each quadrant and consisted of analogs of common prehistoric and historic artifacts (bone, shell, chert, obsidian, pottery, beads [glass and wood], glass, lead, copper, and brass).

Fire behavior observations show that burn plot ignition was achieved via a head fire, driven by a 3-5mph wind, which generated flame lengths reaching 1-2m. Flaming combustion within Plot 1 was observed for approximately 2min40sec, and fuels were 70-90%

consumed as combustion ceased. Time temperature data for Plot 1 are summarized in Figure 2.19. These data show that maximum surface temperatures within quadrants 1-4 ranged between 166.8-310.8 °C. Surface temperatures reached apex levels within approximately 2-3 minutes, and elevated temperatures were sustained for approximately 1 minute. The time / temperature curves for thermocouples 2-4 were very similar, however, the data for thermocouple 1 was somewhat anomalous. Thermocouple 1 recorded a maximum temperature of 310.8 °C and maintained temperature above 200 °C for over 6 minutes before gradually tapering off to below 50 °C after 26 minutes. Fuels in quadrant 1 consisted of 2 medium-sized *Artemisia tridentada*, one of which was partially dead and likely had lower moisture content. Greater potential live and dead fuel mass within quadrant 1 is likely the reason for higher temperatures and broader temperature curve observed for thermocouple 1. Overall, surface temperatures peaked rapidly and diminished to <100°C with varying durations of between 4.5-13.5 minutes. Maximum subsurface temperatures at –1cm and –2cm were 35.1 °C and 26.0 °C respectively, and were only elevated 15-25 °C over baseline values. The results for Plot 1 are consistent with those observed for one individual sagebrush burned during the Jackson Lake Lodge prescribed burn in May of 2002 where maximum surface temperatures ranged between 336.8-163.0 °C, and where temperatures fell to below 50 °C over a period of 20 minutes.

Post-burn analysis of over 50 experimental artifacts showed that all specimens exhibited moderate combustive residue deposits on exposed surfaces. Bone specimens were most prone to the effects of thermal alteration across all quadrants. All specimens exhibited charring and partially combustion on upper surfaces, and existing fissures and cracks were exacerbated by thermal stress. One chert secondary flake from quadrant 3 was thermally fractured, as was a chert nodule from quadrant 1. Peak surface temperatures within these quadrants reached 166.8°C and 310.8°C respectively; however, it is probable that the surfaces of these specimens experienced higher temperatures. In addition, a glass bottle fragment located in quadrant 2, where the peak surface temperature was 193.3°C also exhibited thermally fractures. The results of the artifact analysis combined with recorded temperature data indicate the radiant heat energy emitted by combusting sagebrush is sufficient to elicit thermal fractures in chert materials, glass, and bone. Fracturing of chert and glass was, however, limited only affecting less than 20% of the sample. Charring and enhanced cracking and bone was universal across the entire sample. The deposition of combustive residue on the upper surfaces of experimental artifacts was also pervasive. This compound is a condensate tar produced during pyrolysis and combustion of organic plant material, and is unlikely to significantly impact most archaeological material types.

Plot 2 consisted of a 2x2m burn plot placed within 6 medium-large (1m x 1m, 7cm dia trunk.) *Artemisia tridentada* and associated fine grasses. Fuels in this plot were denser and had greater accumulations of dead fuels (dead under story) compared to the fuels within Plot 1. No experimental artifacts were included in this experiment. Thermocouples 1-6 were placed at the base of one large sagebrush within quadrant 2. The thermocouples were placed in a linear orientation at 3cm intervals beginning with thermocouple 1, which was placed at the base of the sagebrush trunk. The purpose of this experiment was to establish time and temperature data for areas at the soil surface beneath the canopy of large sagebrush.

The time/temperature data for Plot 2 are summarized in Figure 2.20. Results of this experiment show maximum temperature ranging between 238.7-522.2 °C. Flaming combustion was observed in the plot for approximately 7 minutes with flame lengths reaching the 1-2m range. Post-fire combustion of fuels within the plot was estimated at 90%. Time and temperature curves for thermocouples 2-6 were very similar with temperatures peaking rapidly to over 450 °C, and falling off gradually to 50 °C over a period of 43 minutes. Temperature for thermocouples 2-6 were maintained above 400 °C for 6 minutes, above 300 °C for 9 minutes, and above 200 °C for up to 18 minutes. Thermocouple 1 produced the only anomalous recording with a maximum temperature of 238.7 °C and gradual curve that dropped to 50 °C within 30 minutes. This thermocouple was positioned next to the sagebrush trunk, which did not combust as consistently as its dead under story. The dead under story associated with thermocouples 2-6 did combust uniformly and completely resulting in higher maximum temperature peaks and exposure to longer periods of temperatures above 200 °C under the time temperature curve.

This experiment demonstrates that dense accumulations of large sagebrush with significant accumulations of dead under story can produce maximum soil surface temperatures above 500 °C accompanied by protracted temperature curves. The amount of radiant heat energy emitted within Plot 2 would have been sufficient to produce significant thermal stress in many classes of archaeological material, particularly bone, shell, and cherts.

The results of the overall experiment show that sagebrush fuels are variable, however, even the lower end of the spectrum archaeological materials positioned at the soil surface beneath the under story of sagebrush are subject to thermal damage. The degree of thermal alteration is variable as well and depends largely on artifact class, fuel load/composition, position of artifact relevant to fuels, and fuel combustion characteristics.

PIÑON-JUNIPER EXPERIMENT

Field based experimentation focused on assessing the impact of prescribed burning on archaeological resources was also conducted in a piñon-juniper environment during the East Douglas Creek prescribed burn project on BLM lands in northwestern Colorado. The experiment consisted of one 2x2m burn plot containing two immature live piñon, two dead/decayed logs, and a thin 1-2cm duff and small litter accumulation. Approximately 50 experimental artifacts, representing the same range of material types included in previous experiments, were distributed equally within each of the four 1m^2 quadrants encompassed within the burn plot. Artifacts and thermocouples were placed on the mineral soil surface at the center of each quadrant in association (5-20cm) with the logs, but not directly beneath them. Temperature data were recorded at the soil surface within each of the quadrants, and at 0cm and –5cm beneath one of the logs using the primary OM3000 system.

Results

Fire behavior observations showed that the fire in the vicinity of the burn plot was severe. The plot was burned via a head fire pushed by a 6-10 mph wind, which generated 20-30ft flame lengths as large dead ground fuels were ignited and live piñon-juniper fuels torched into the crowns. Large flames and torching continued for several minutes. Post-fire, log fuels and duff within the burn plot were 100% combusted and live fuels were completely torched. Patches of soil within and near the burn plot were oxidized to a strong orange color. The fire was sufficiently intense to destroy the protective fire box that contained the data logger and rendered the LCD screen on the data logger unreadable for several hours. This burn was considerably more intense than that encountered during any of the previous prescribed fire experiments.

Time/temperature data for the experiment are summarized in graphical form in Figure 2.21. These data show that peak surface temperatures within the burn plot ranged between 722.3-853.0°C. Peak surface temperatures were achieved very rapidly within 1 minute within each of the four quadrants. Interestingly, temperatures then fell rapidly to the

400°C range within 1-2 minutes, and were sustained within the 200-400°C range for at least one hour. Data were not recorded beyond that point due to an inadvertent cessation of the data logger caused by the blacked-out LCD screen on the unit. Based on analysis of the time/temperature curves, it is highly probable that elevated temperatures could have been sustained for a protracted time period. The peak surface temperature directly beneath one of the logs reached 814.3°C, and interestingly, the –5cm reading beneath the log peaked at 527.3°C. These values also peaked rapidly within 1 minute and then declined precipitously to <100°C within 1-2 minutes. However, heating directly beneath the log began to rise again after approximately 50 minutes, reaching a high point of 265.5°C before data recording was terminated. This is likely due to renewed combustion of the remaining portion of the log at some point during the experiment. These data clearly indicate that burning within a piñon-juniper environment is capable of producing severe temperature gradients at the soil surface as well as –5cm subsurface.

The results of the artifact analysis show that significant thermal alteration was pervasive across the majority of the sample. All bone specimens were heavily charred, combusted, fractured, and extremely friable. Each of the four Hartville Uplift chert nodules exhibited significant degrees of thermal fracturing and mineral oxidation (yellow-brown to red, limonite to hematite). Fragments of some nodules were located up to 50-60cm away from the location of the main body. All four Pecos chert secondary flakes also exhibited thermal fractures, but not as extensive as that observed for the chert nodules. Each obsidian secondary flake exhibited enhanced radial fracture lines a slight metallic sheen on upper surfaces. Two glass specimen also sustained thermal fractures, copper specimens exhibited a flakey exfoliation of out surfaces, and lead specimens were completely melted and deformed. Specimens that did not experience structural damage included 2 glass specimens, all pottery sherds (black-on-white), and all phosphoria flakes. However, the entire sample exhibited deeply blackened combustive residue deposits on exposed surfaces. Thermal alteration of artifacts during this experiment was more pervasive and severe than that observed during any of the previous prescribed fire experiments.

These data suggest that combustion of piñon-juniper fuels is volatile, flashy, and capable of generating extreme temperature gradients at the soil surface and within the first 5cm of soil where logs are present. Archaeological materials located at the soil surface are likely to exhibit significant thermal damage when burned under similar conditions described for this experiment. Materials most at risk include bone, shell, glass, chert (particularly large specimens), and lead. Unfortunately, only one trial was conducted during the burn due to situational restrictions. Additional data regarding the characteristics of prescribed burning in piñon-juniper environments is needed to assess the results presented here.

SUMMARY AND CONCLUSION

This research project was focused on assessing the impact of prescribed fire on archaeological resources through field-based experimentation conducted in conjunction with prescribed burning projects on federally managed lands. Prescribed fire is a common and effective resource management tool utilized to reduce hazardous fuels and promote healthy ecosystems. This project was focused on assessing the potential impact of prescribed burning on archaeological resources. Research was conducted under several different fuel models to include; mixed grass prairie, mixed grass prairie / ponderosa, mixed conifer, riparian, sagebrush, and piñon-juniper. The results of the experiments show that the impact of prescribed fire on archaeological resources is variable and largely dependent on fuel model, fire behavior, peak soil surface temperature, duration of heating, and artifact class. Moreover, the results suggest the prescribed burning may be performed with limited risk to the archaeological materials in some instances; however, it is critical that large fuels be reduced in the vicinity of important resources in order to mitigate significant thermal alteration of multiple artifact classes. Table 2.1 provides a generalized data summary for each of the prescribed fire experiments.

Table 2.1: Prescribed burn experiment summary data (generalized).

Fuel Type	Peak Temp (Surface)	Residence Time	Fire Effect (Experimental Artifacts)
Mixed Grass	100-300°C	10-20 sec	Light CB, limited bone PC only
Grass/Mixed Conifer (Grass) (Grass/Litter) (Log)	 100-300°C 250-500°C 450-600°C	 10-20 sec 5-15 min 5-20 min	Grass: light CB all, limited bone PC Grass/Litter: moderate CB all, bone PC, FR Log: extensive bone FR, PC, sherd SP, glass FR, Lead MLT, shell DL, heavy CB all
Riparian (Grass) (Willow Sm.) (Willow Lg.)	 100-200°C 100-300°C 300-500°C	 10-20 sec 1-2 min 2-8 min	Grass: light CB all, limited bone PC Sm. Willow: light CB all, limited bone PC Lg. Willow: moderate CB, bone PC, glass FR
Sagebrush (Small-Med) (Large)	 150-300°C 250-500°C	 1-3 min 2-4 min	Sm-Med Sagebrush: moderate CB all, bone PC, limited FR, chert nodule limited FR, lead MLT Lg Sagebrush: No artifact data
Mixed Conifer (Duff/Litter) (Log)	 200-400°C 400-800°C	 1-2min 5-20 min	Duff/light litter: heavy CB all, bone PC and FR Log: chert FR, PL, FR, phosphoria PL, SP, obsidian CRH, lead MLT, glass FR, bone severe PC, FR
Piñon-Juniper (Large Litter)	700-800°C	2-4 min	Large litter: severe chert FR, OX, severe bone PC, FR lead MLT, glass FR, shell DL, PC

Thermal Alteration Codes Definitions: CB = Combustive Residue, PC = Partial Combustion/Charring, FR = Thermal Fracture, SP = Thermal Spalling, OX = Mineral Oxidation, MLT = Melting, DL = Delamination

Research at Badlands National Park addressed the potential impact of cool-season prescribed fire within grassland fuels on a variety of common archaeological materials. The results of these experiments indicated that grassland fuels did not provide sufficient biomass to sustain high temperatures and long residence times at the soil surface and certainly not below the soil surface. Maximum surface temperatures from 17 individual experimental trials averaged 161.8°C, and the average subsurface maxima were 28.6°C at –1cm and 11.4°C at –2cm (average increase of 13.4-7.7°C over baseline). However, the results of the experiments also show that peak surface temperatures within a $2m^2$ burn plot can vary considerably from only 80 °C to nearly 400 °C depending on the combustion consistency of fuels within each quadrant. In general, heating was characterized by precipitous ascent to apex levels within 30-60 seconds with near peak values being sustained briefly for 10-15 seconds, followed by a decline in temperature to <50°C within 3-9 minutes depending upon fire behavior. Peak temperatures recorded on the upper surfaces of artifacts averaged 189.3°C, and lower surface maxima averaged 92.1°C, resulting in an average temperature differential between the two surfaces of 97.2°C (49%).

Overall, the relatively low surface temperatures and short residence times associated with the combustion of grassland fuels generated minimal thermal alteration of experimental artifacts deposited at the soil surface. The most pervasive form of thermal alteration affecting artifacts was the presence of condensate tar deposit formed during the pyrolysis and combustion of organic fuels. It is likely that over time, these tar deposits will weather from the surfaces of artifacts since the residue was removed relatively easily in the laboratory using water and a pumice soap solution. Artifact classes with organic components such as bone, and those that are completely organic such as wood did exhibit minimal partial combustion along edges and upper surfaces. No catastrophic forms of thermal alteration such as thermal fracturing, spalling, deformation, or surface cracking were observed during the series of experiments performed at the park during 2001 and 2002. The results of the experiment demonstrate that early-season prescribed burning in mixed grass prairie environments will have a minimal impact on archaeological materials located at the soil surface. Archaeological resources located greater than 1cm subsurface will be largely unaffected under the same conditions. These results are consistent with that reported by Brunswig et al. 1995, and that reported by Sayler et al. 1989 for low fuel load burn plots. In sum, cool-season prescribed burning in grassland fuels will produce low peak surface temperatures characterized by brief residence times, which in turn, will generate limited potential for significant thermal alteration of surface artifacts and no thermal alteration of subsurface archaeological deposits.

Experiments conducted at Wind Cave National Park in mixed grassland and ponderosa fuels illustrate more fully the direct relationship between fuel type, temperature, and the impact of heat energy on archaeological materials. The results of the experiments show that combustion of grass fuels produced limited peak temperatures and brief residence times, which in turn, had a minimal impact on experiment artifacts (combustive residue deposition). Heating in grass fuels was precipitous and brief, generating a maximum temperature of only 92.0 ˚C within 1-1.5 minutes with elevated temperatures being sustained briefly for only 10-20 seconds. Heavier litter and log fuels generated peak temperatures of >600°C for log fuels and >400°C for litter fuels. Litter fuels sustained temperatures of 200-400°C for up to 20 minutes, and log fuels sustained temperatures >500°C for approximately 20 minutes as well. The thermal alteration of experimental artifacts associated with these fuels was most prominent for organic specimens such as bone, shell, and wood. These materials exhibited heavy charring/combustion, thermal fractures/fissures, and a pronounced increased in post-fire friability. In addition, thermal spalling/fracturing of pottery sherds and glass, and melting of lead specimens was observed within in some burn plot quadrants, particularly those experiencing sustained heating. Where prescribed burning in planned for mixed grass prairie and Ponderosa environments, minimal impact to surface artifacts located within grassland fuels can be expected; however, direct association of archaeological materials with large dead and downed conifer fuels during burning is likely to generate significant thermal damage among some artifact classes, particularly bone, shell, and glass. Removal of large fuels from known archaeological sites would be the course of action to mitigate the impact of prescribed fire in forested areas. Known sites within grassland contexts could be treated to mitigate fire intensity or allowed to burn depending on the discretion of cultural resource managers.

The results of several experimental trials conducted in a mixed conifer environment within the Pike National Forest suggest that surface heating beneath combusting logs is characterized by prolonged periods of sustained high temperature, and protracted declines in temperature over several hours. Peak soil surface temperatures recorded beneath combusting generally ranged between 400-800°C depending on log size and extent of combustion. Temperatures in excess of 200°C can be sustained for several hours. Most archaeological materials in direct associated with combusting logs will sustain a significant thermal damage, this is particularly apparent for bone, shell, lead, and chert artifacts. Conversely, soil surface heating beneath duff is characterized by rapid ascent to 200-400°C accompanied by brief residence time and abrupt decline in temperature. Significant thermal alteration of archaeological materials associated with duff is less probable and generally limited to those material types with organic components such as bone. These results further illustrate the important relationship between fuel load, energy output, and duration of heating at it related to the thermal alteration of archaeological materials. Clearing large fuels from known archaeological sites and avoiding important or particularly vulnerable archaeological sites during prescribed burns in mixed conifer environments would be the most appropriate means by which to mitigate potentially negative fire effects.

Prescribed burning in a riparian environment at Grand Teton National Park was shown to have a limited negative impact on archaeological materials. Here the impact of burning fuels on archaeological materials is generally mitigated by high soil and fuel moisture content. Peak soil surface and upper artifact surface temperatures associated with grass and small willow fuels varied significantly between 90-350°C. Heating was characterized by rapid ascent to apex levels, short residence time, and rapid decline. Subsequently, thermal alteration of experimental artifacts was limited to light combustive residue deposition. Where significant combustion of large willows occurs, peak soil surface temperatures directly at the base of the willow may reach the 400-500°C range. Significant thermal alteration of artifacts in this instance is possible; however, only thermally spalled glass and charred bone was observed during the experiment. Overall, the probability of riparian zone prescribed fire significantly impacting archaeological materials is low, and largely dependent on complete combustion of large fuels and the direct association surface artifacts with such fuels. The major concern regarding prescribed burning in riparian zones is the heat energy generated by large willow species during combustion. In order to mitigate the potential negative of prescribed burning on archaeological resources, large fuels should be removed from known sites. Archaeological sites located within areas dominated by fine fuels are unlikely to be significantly impacted during burning, and the thermal alteration of subsurface archaeological deposits is improbable due to high soil moisture content.

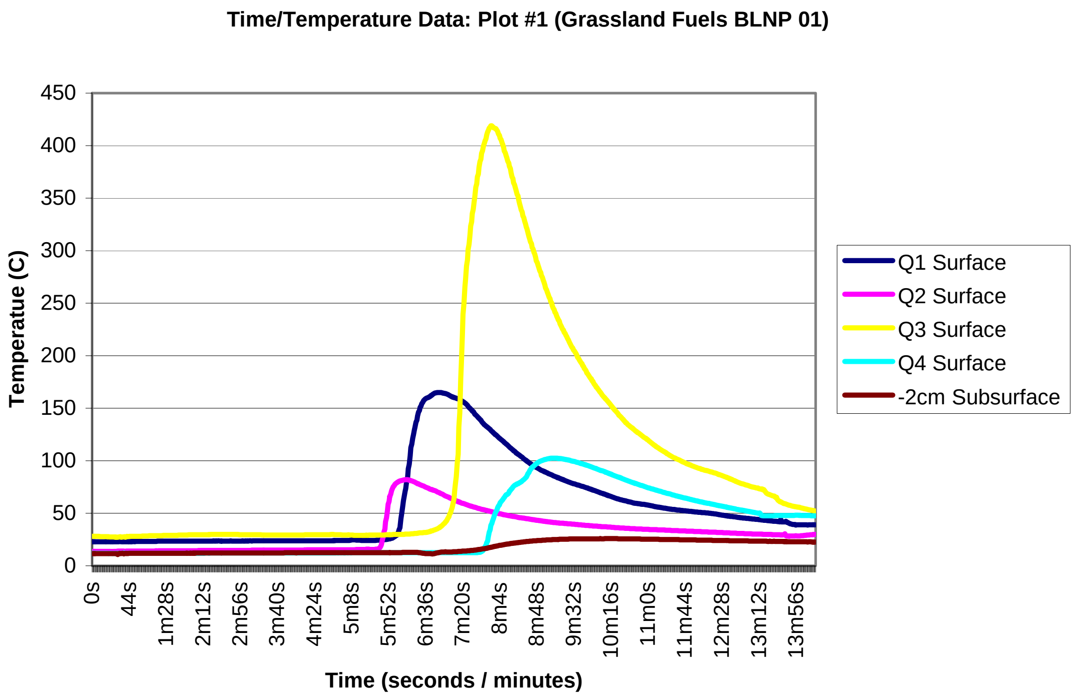
The impact of prescribed burning in sagebrush communities on archaeological resources is variable and largely dependent on the size and density of sagebrush, the proximity of artifacts to sagebrush understory, and artifact class. The results of the experiment conducted at Grand Teton National Park show that peak surface heating generated by combusting sagebrush can vary from 450-520°C for larger and densely sagebrush; and 160-310°C for smaller more dispersed accumulation of sagebrush. Although experimental artifacts were not burned in association with large/dense sagebrush fuels, it is likely that significant thermal alteration of bone, glass and chert would occur if these materials were located within the understory of the vegetation. During the experiment conducted within a burn plot containing smaller and more dispersed accumulations of sagebrush these artifacts types were impacted by charring, thermal fracturing, and thermal spalling. However, significant thermal alteration if likely to affects only surface artifacts located directly beneath the understory of sagebrush. Thermal alteration of subsurface archaeological deposits within sagebrush communities is improbable. Mitigating the impact of prescribed burning in this fuel type on surface archaeological materials could be accomplished by fuel thinning in the vicinity of know sites.

The prescribed burn experiment conducted in piñon-juniper fuels in northwestern Colorado generated the most extreme temperature gradient recorded during the entire project. Peak surface temperatures during the experiment reached the 720-850°C range with temperatures of 200-400°C being sustained for an hour thereafter. The subsurface peak temperature recorded –5cm beneath a small log reached 527°C. Significant thermal alteration of experimental surface artifacts was pervasive with the most profound thermal damage affecting bone, chert, and glass specimens. Unfortunately, only one trial was conducted in piñon-juniper fuels; however, the results of the experiment show that combustion of these fuels is volatile and capable of producing extreme temperature gradients that can significantly impact most archaeological material types. Further research is need to validate the results of this experiment and to offer specific recommendations regarding the mitigation of potential negative effects to archaeological resources during prescribed burning in this fuel type.

In sum, the proportion of the radiant heat energy generated by combusting fuels that is transmitted downward to the soil surface and surface artifacts is very important in assessing the potential for thermal alteration of archaeological materials. Heavy fuels combust at higher temperatures and have longer residence times compared to light fuels such as grasses. The physical composition and thermal properties of an artifact also condition the potential impact of radiant heat energy. Some artifacts, due to their physical structure, are more resistant to thermal alteration. However, the results of the study do indicate that heat significantly affects the structural integrity of bone, and some lithic types, particularly chert. Heavily burned bone was appreciably more friable post-heating, which can have significant implications for the long-term preservation of thermally altered archaeological bone. In addition, severe thermal fracturing of chert flakes and nodules was also observed under high fire severity. In some instances, fragments of chert nodules were recovered 50-60cm away from the body of the original specimen. In addition, Hartville and Pecos chert specimens also exhibited heat-induced color alteration to distinctively different colors due to mineral oxidation under high fire severity. Explosive thermal fracturing and mineral oxidation may have significant implications for accurately identifying lithic material types and for refitting studies.

In brief, the important variables to consider when assessing the potential impact of prescribed fire and wildland fire on archaeological resources are: 1) fuel load; 2) fire behavior; 3) peak temperature and duration of heating; 4) proximity of artifacts to fuels; and 5) class of artifact. The research presented here has been limited to the immediately discernable effect of heat energy on artifacts. The long-term impact of thermal alteration of artifacts such as the potential for increased weathering and decreased preservation potential has not been addressed.

Figure 2.1



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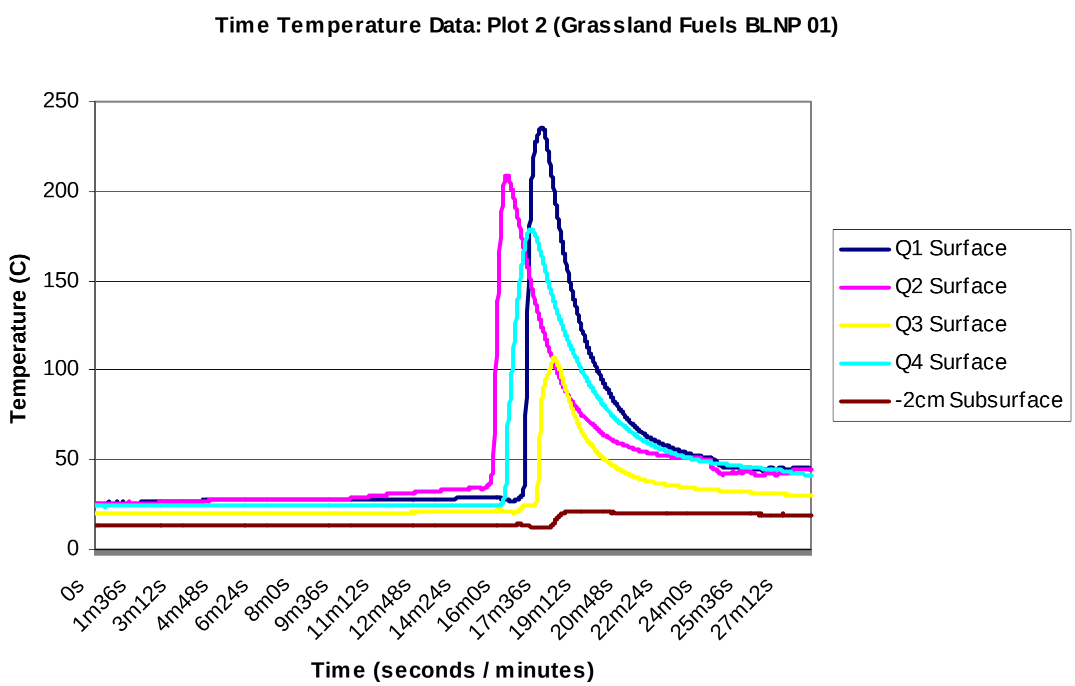

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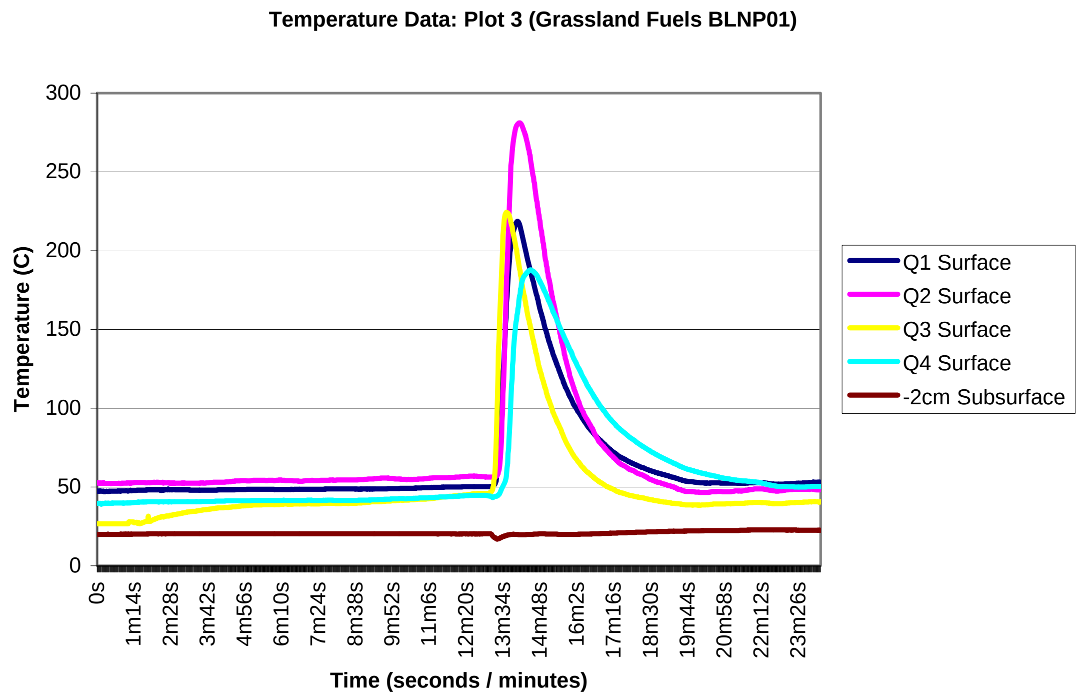

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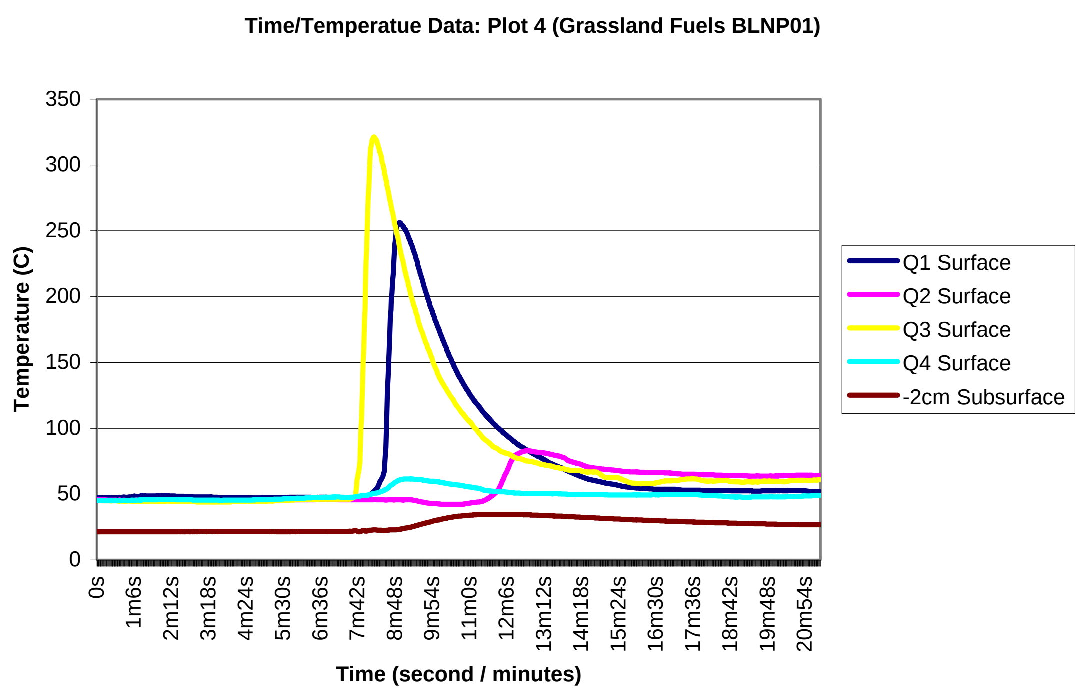

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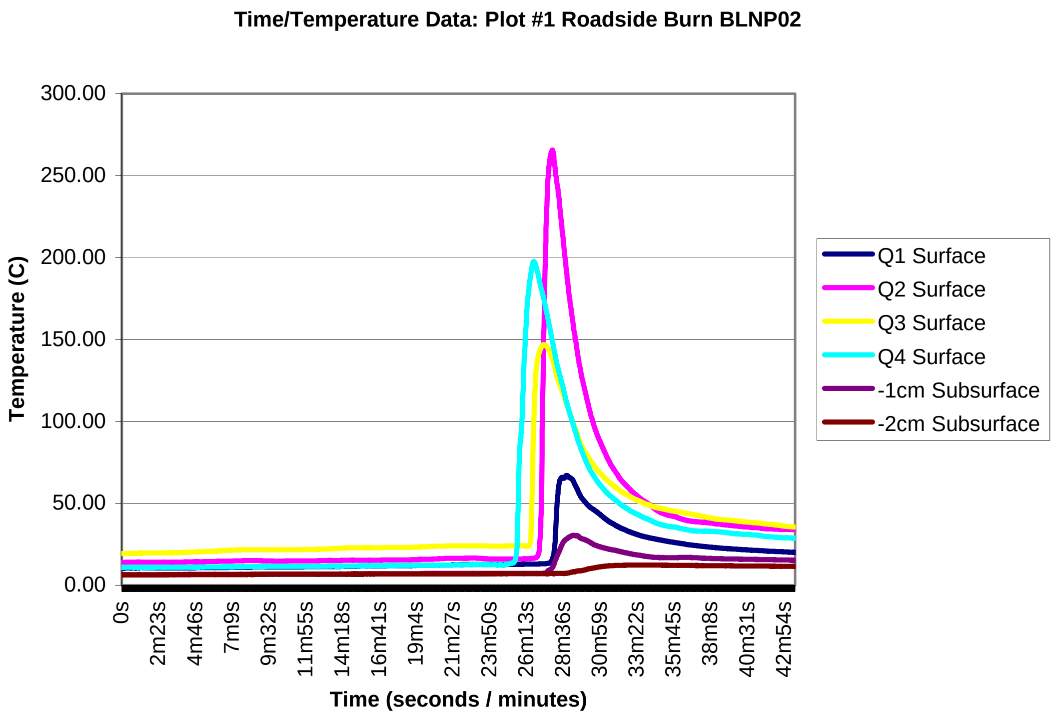

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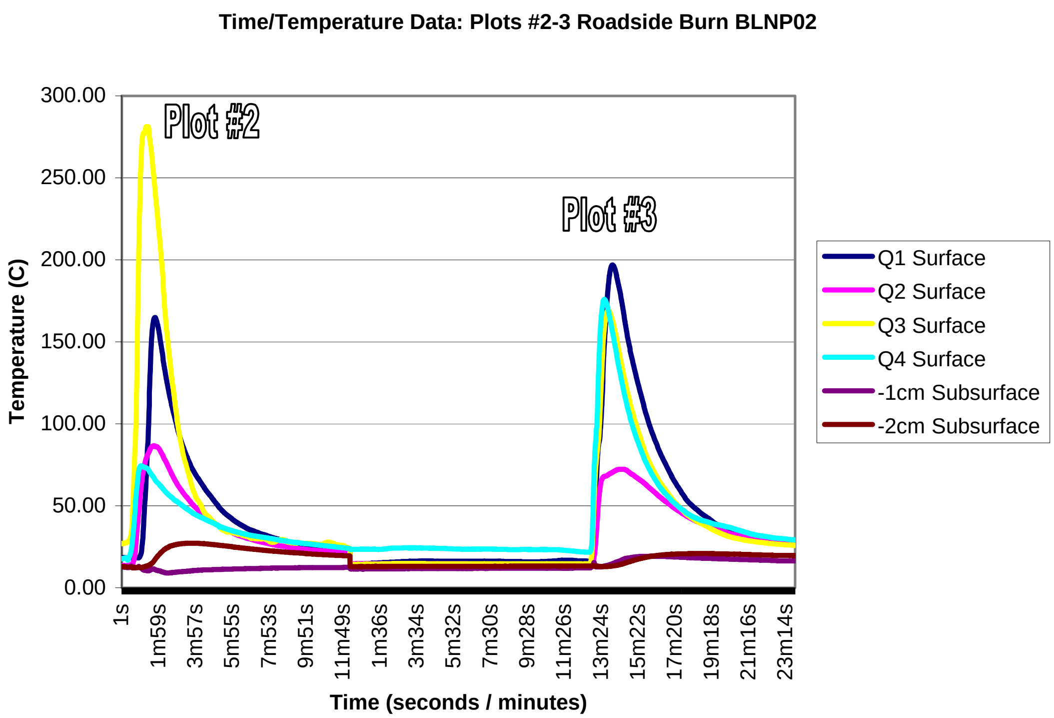

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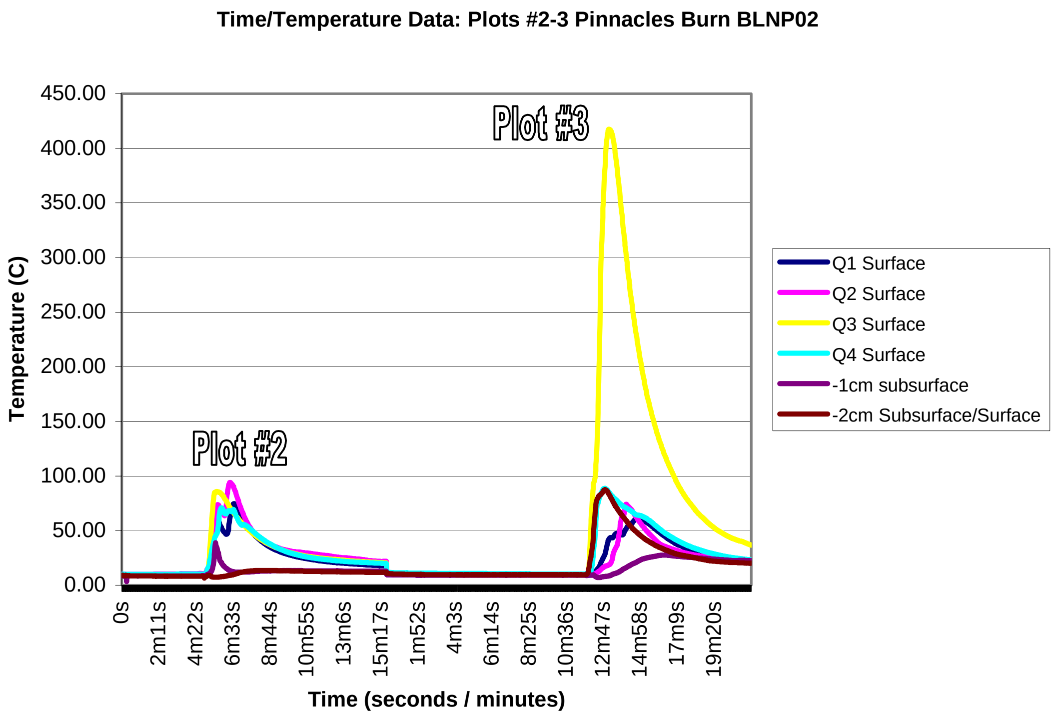

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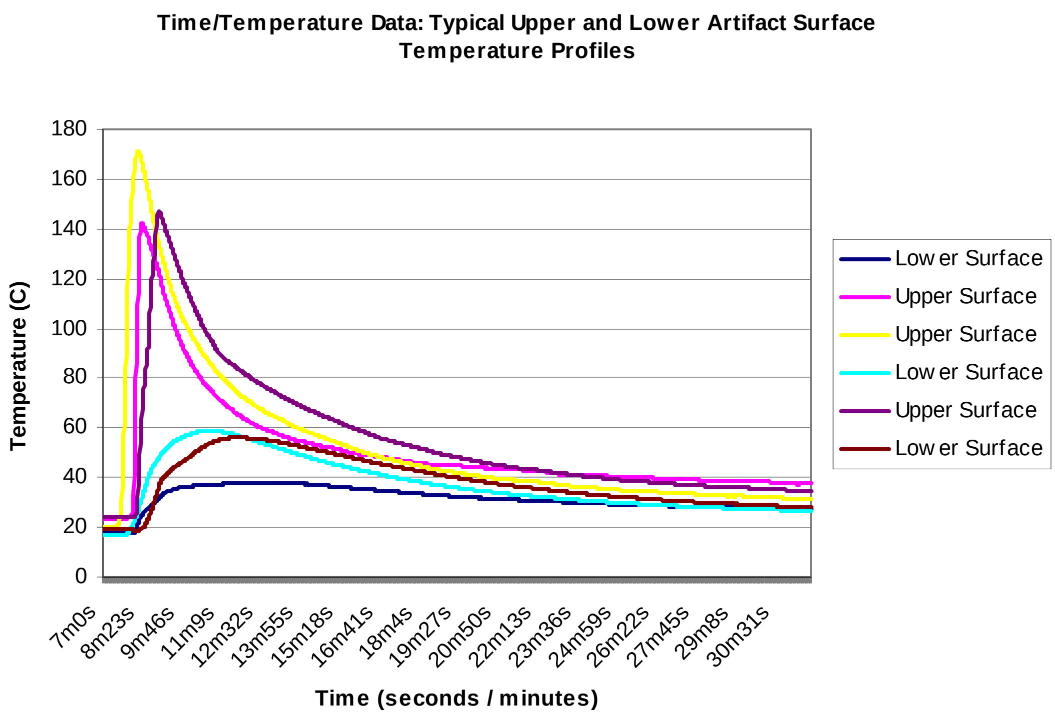

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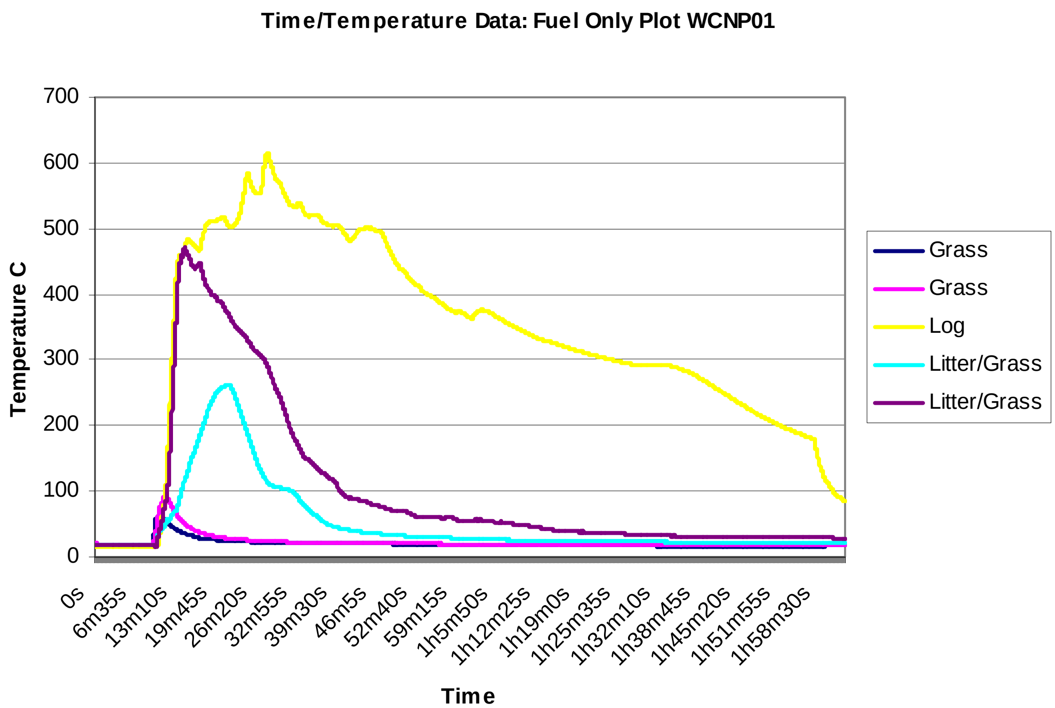

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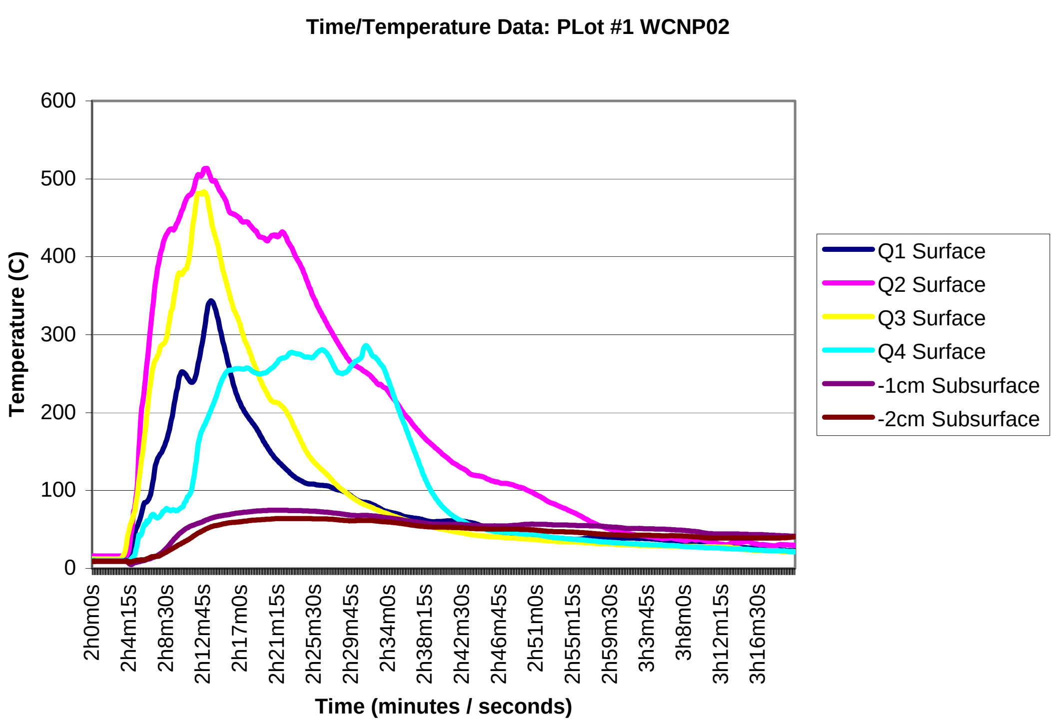

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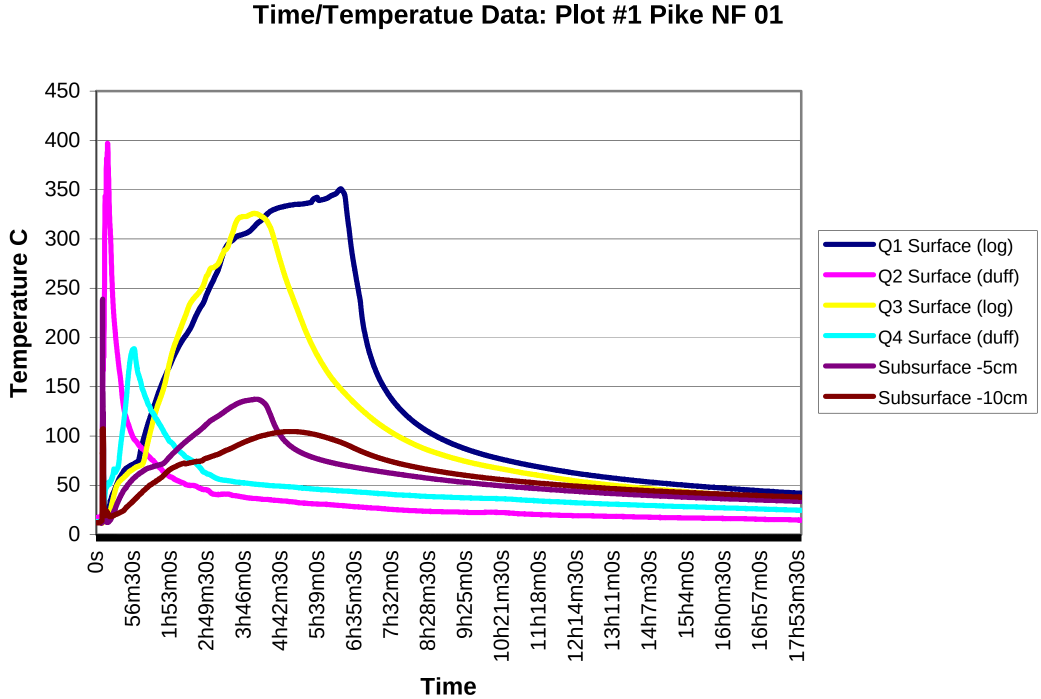

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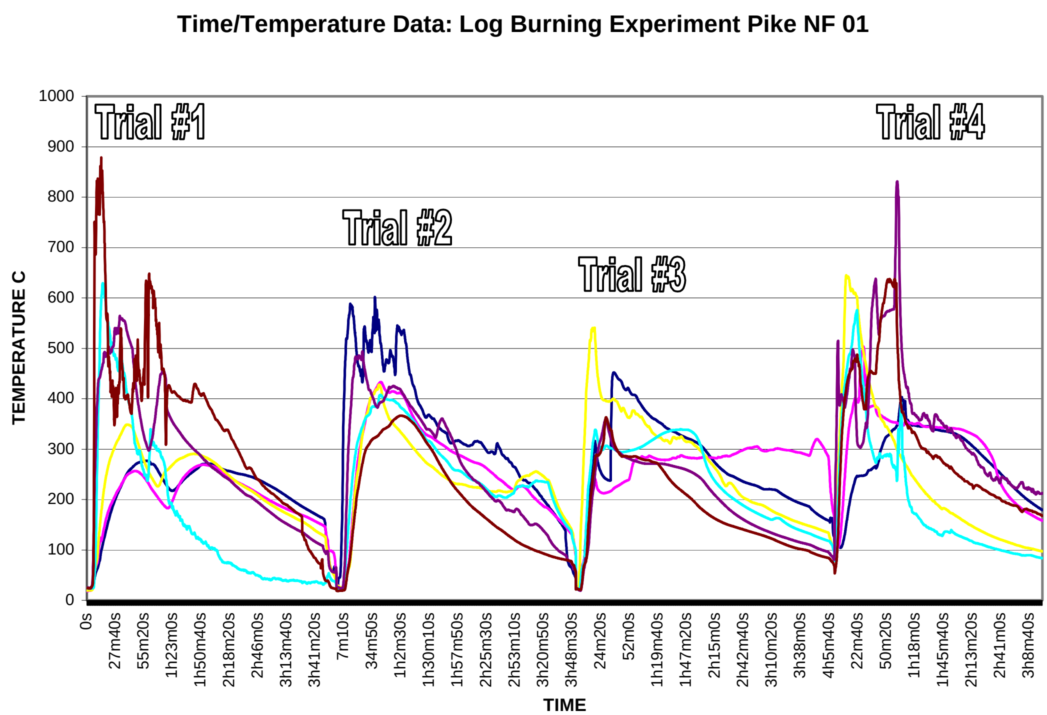

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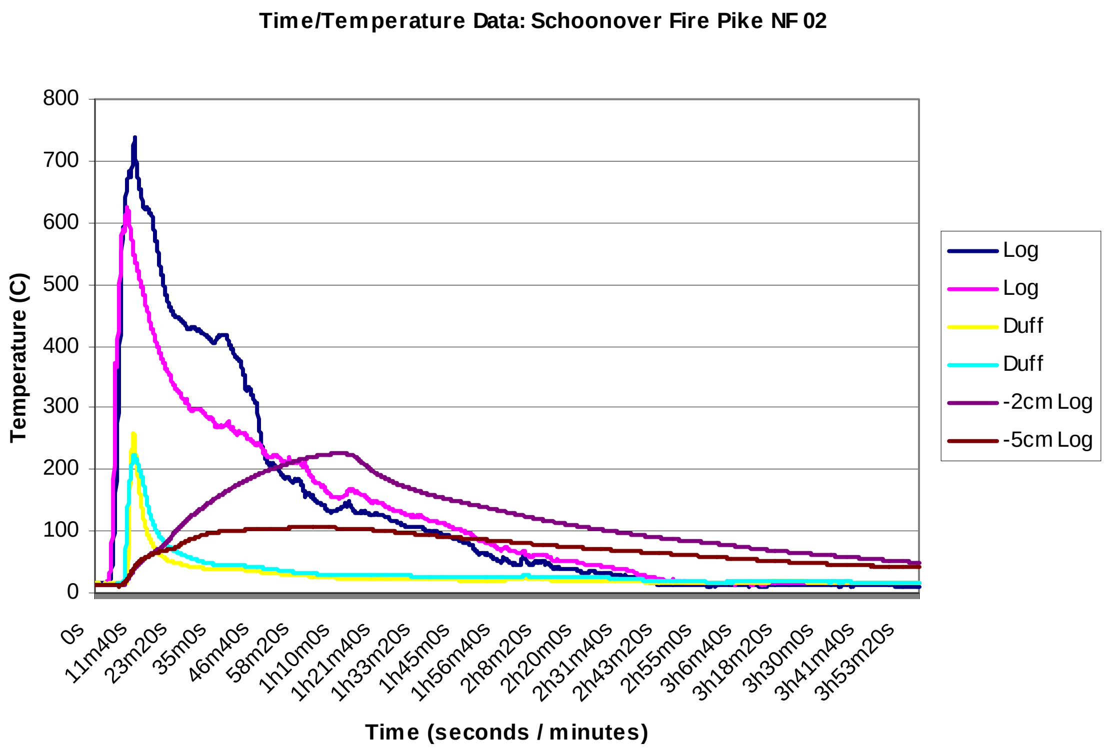

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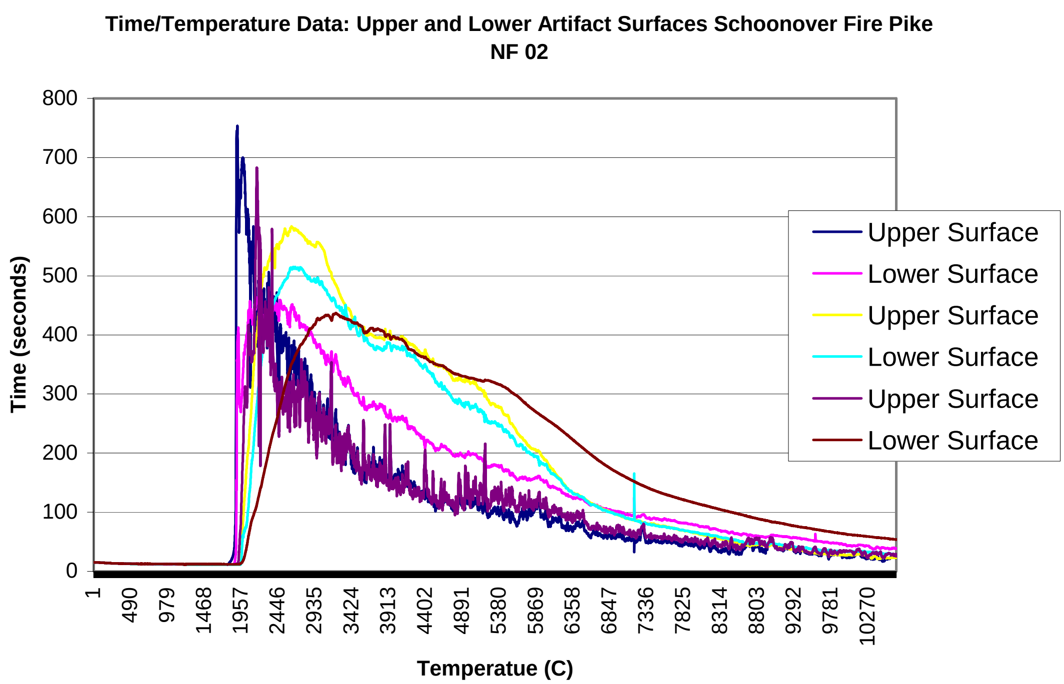

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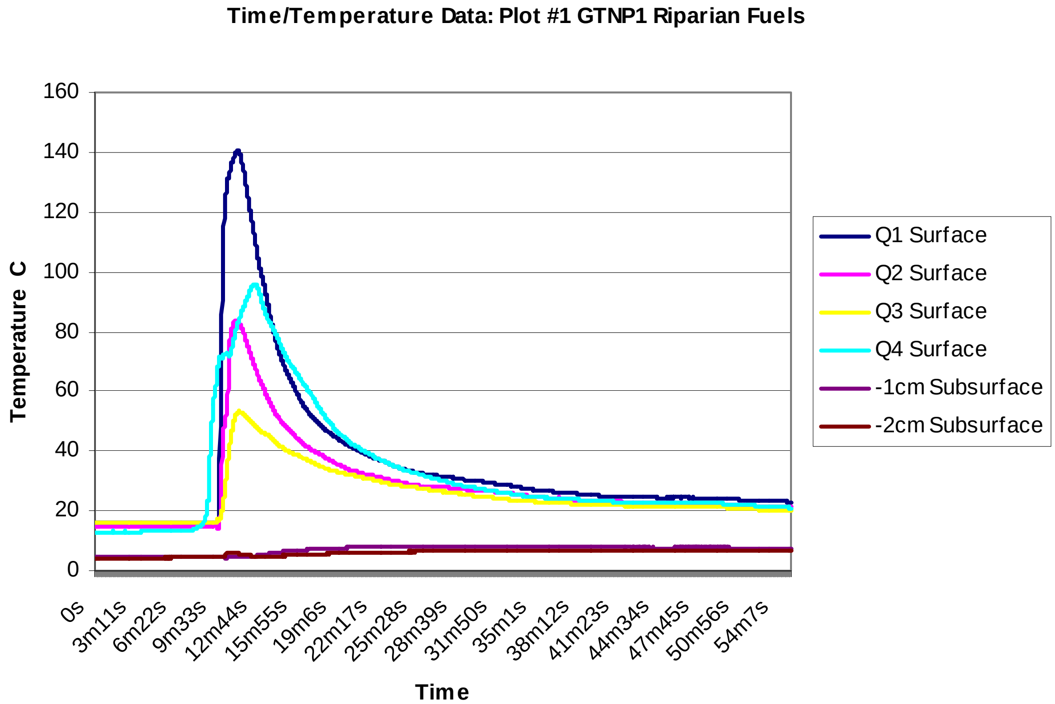

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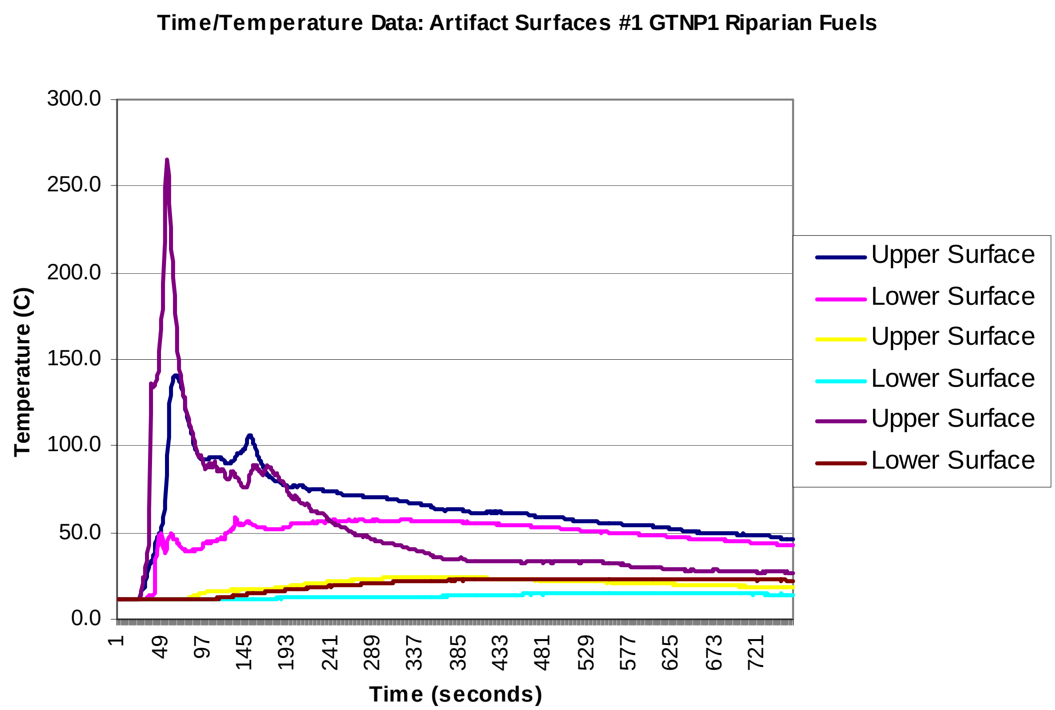

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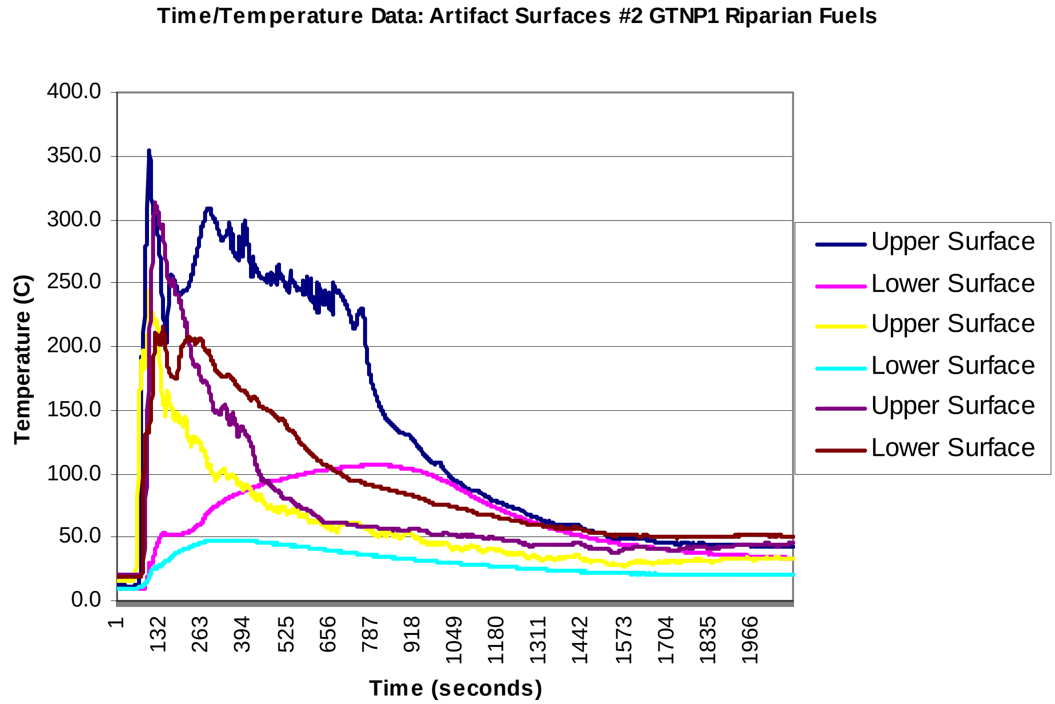

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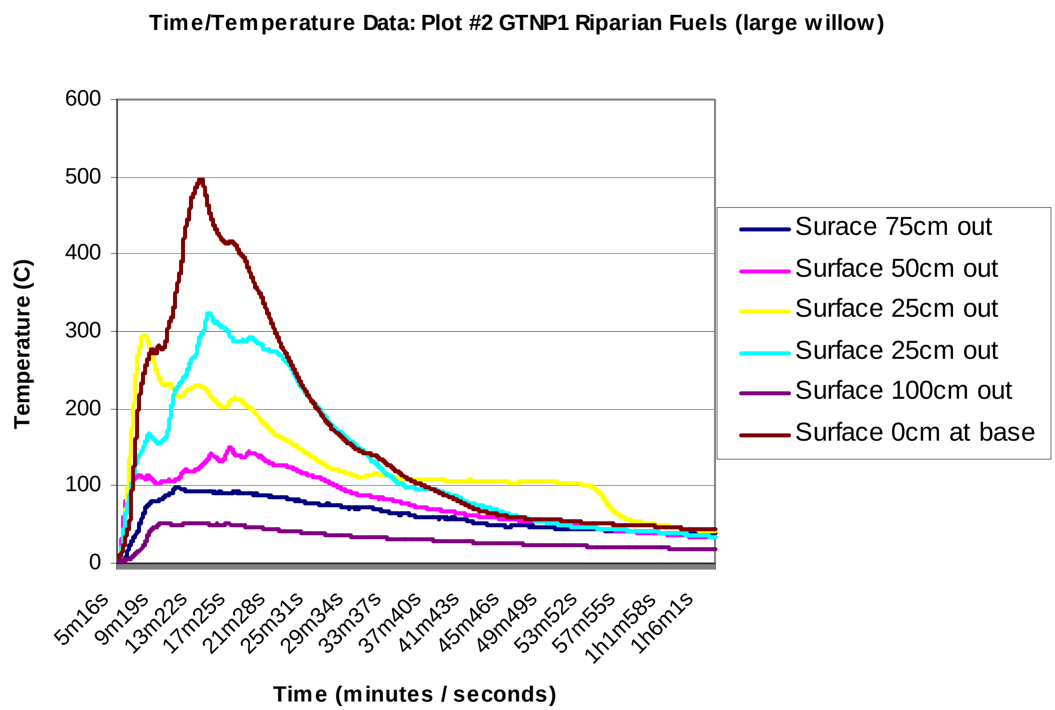

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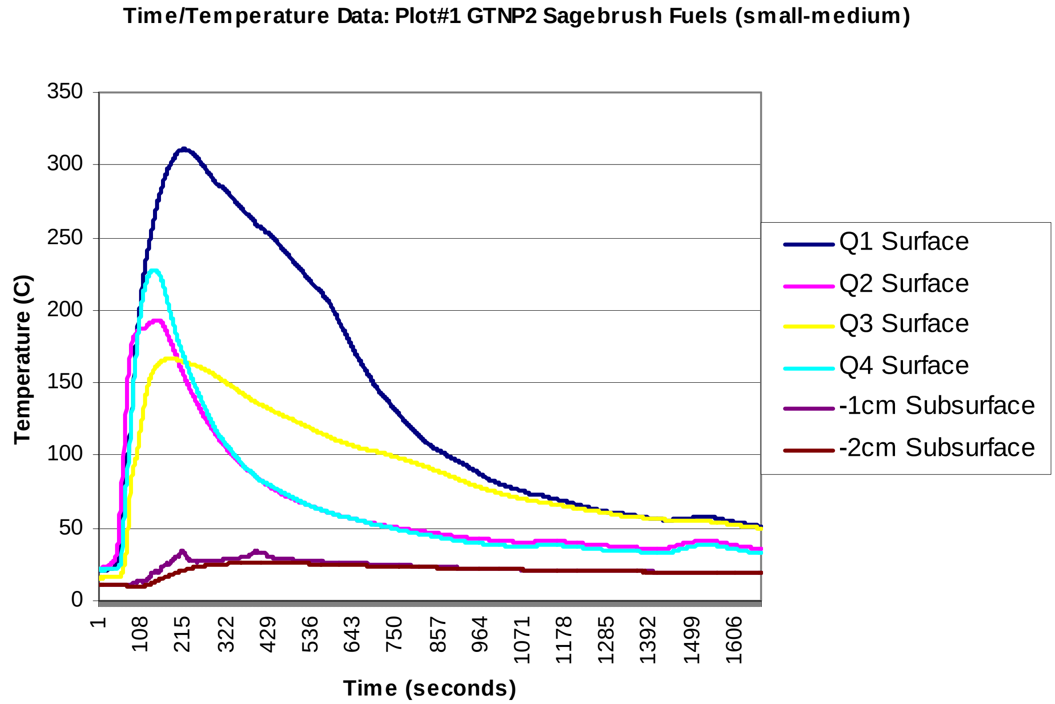


Figure 2.20

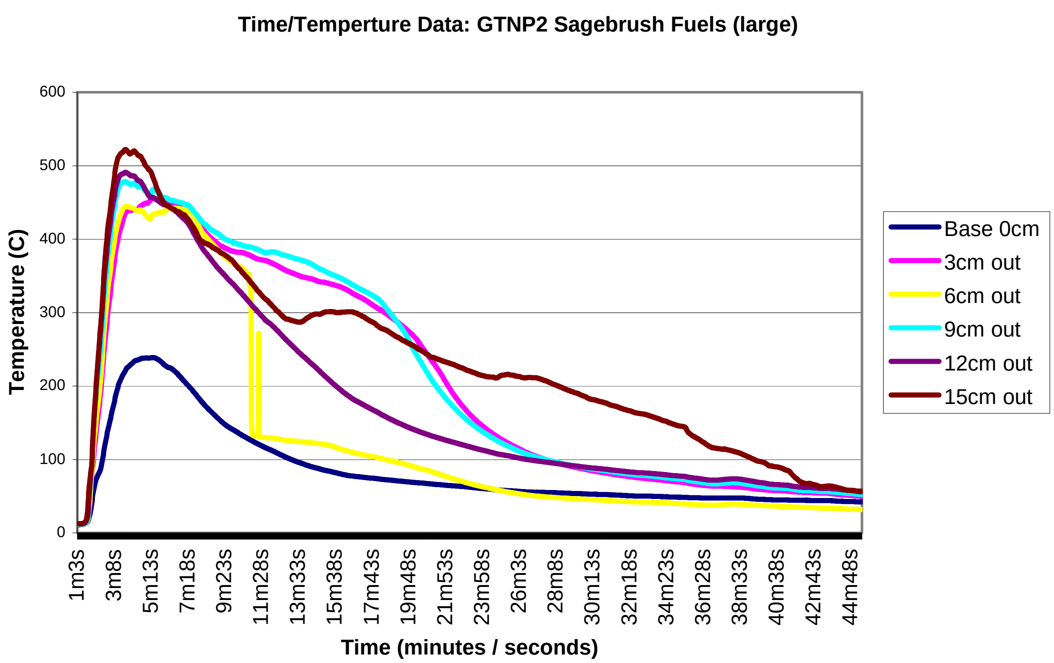
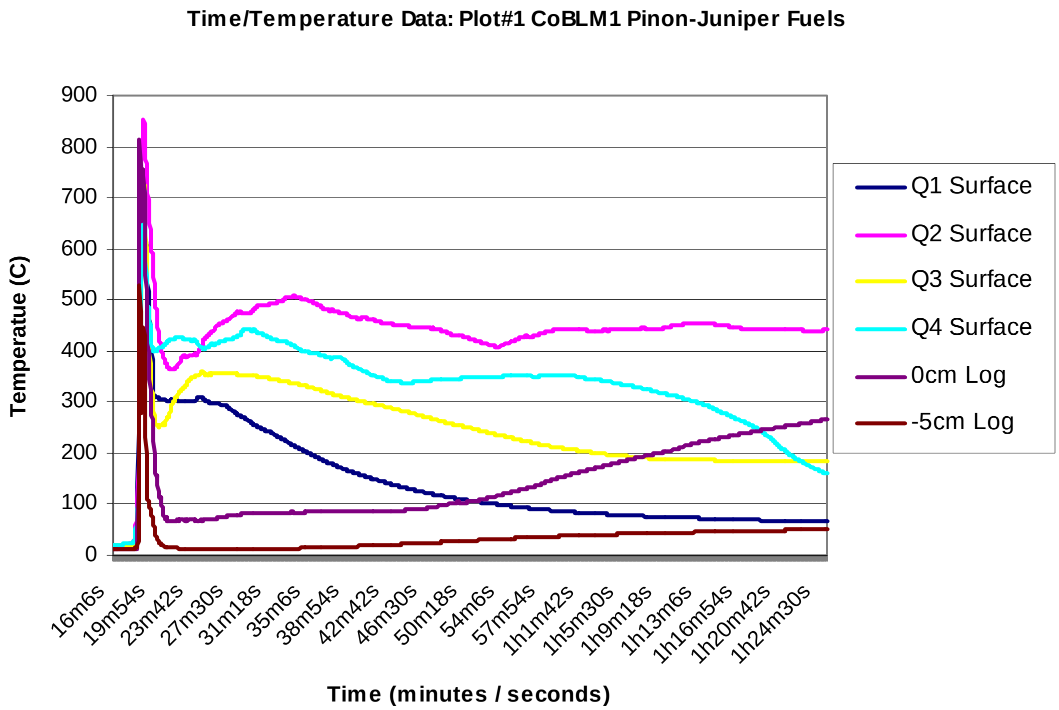


Figure 2.21


Time/Temperature Data: Plot#1 CoBLM1 Pinon-Juniper Fuels
Temperatue (C)
900
800
700
600
500
400
300
200
100
0
16m6s
19m54s
23m42s
27m30s
31m18s
35m6s
38m54s
42m42s
46m30s
50m18s
54m6s
57m54s
1h1m42s
1h5m30s
1h9m18s
1h13m6s
1h16m54s
1h20m42s
1h24m30s
Time (minutes / seconds)
Q1 Surface
Q2 Surface
Q3 Surface
Q4 Surface
0cm Log
-5cm Log

CHAPTER 3

LABORATORY FURNACE HEATING OF SELECTED MATERIALS TYPES

Introduction

Previous research incorporating laboratory experimentation to explicitly address the potential for thermal alteration of archaeological materials during wildland and prescribed fires is very limited. Steffen (2002) utilized laboratory-heating experiments to replicate the range of thermal alteration observed on obsidian artifacts burned during the Dome Fire in the Jemez Mountains of northern New Mexico. In addition, Nakazawa (1998; 2002) conducted similar laboratory experiments to study thermally altered obsidian artifacts burned in cultural contexts. These studies offer significant insight into the processes involved in the thermal alteration of obsidian. However, their research was limited to obsidian artifacts only, and few researchers have used laboratory experimentation to address the impact of natural fire across a broader range of archeological materials.

Kelly and Mayberry (1980) briefly outlined a research design involving the heating of archaeological materials representing a variety of artifact classes using an electric laboratory furnace. Kelly and Mayberry (1980:605) state that the "tests have not yet begun", and it is unclear if these experiments have been conducted since no further reference has been identified from the literature. Bennett and Kunzmann (1985) conducted the only published research project involving the laboratory heating of a wide range of archaeological materials. In their experimental design, cryptocrystalline quartz (cherts, flint, and chalcedony), obsidian, Southwestern pottery sherds (slipped/decorated, undecorated, and corrugated), stoneware, china, modern glass (window, and bottle), enameled tin ware, and bone ("fresh" and "old") were heated in an electric muffle furnace to various temperature ranging between 200-800°C over a period of several hours. Heated specimens were assessed for macroscopic thermal alteration as well as weight loss by calculating the difference between the total weight loss of a specimen (after heating trials), and the loss of chemically bound water (pre and post-trial via infrared spectrophotometer). In addition, thermal shock testing was also conducted whereby heated specimens were submerged in water while specimen temperature and evidence of stress-induced failure (cracking, spalling, checking) were recorded.

The results of Bennett and Kunzmann's experiment showed that chert specimens experienced post-heating weight loss, largely attributed to the release of chemically bound water and capillary water. Weight loss was reported to be gradual between 200-600°C, and precipitous at temperatures of 600-800°C. The only other observable thermal alteration of cherts documented in the experiment was surface dulling of specimens heated to 600-800°C. No catastrophic forms of thermal alteration such as thermal fracturing, potlid fracturing, or surface crazing were observed by the researchers. This observation is inconsistent with the literature surrounding the heat treatment of chert where several researchers have reported heat-induced mineral alteration, and in some instances, thermal fracturing and crazing among various types of chert at temperatures between 300-500°C (Ahler 1983; Griffiths et al. 1987; Schindler et al. 1982; Purdy 1974; see also Luedtke 1992 for a summary).

Bennett and Kunzmann suggest that weight loss in cherts and flint is a function of time and temperature, and derived a hyperbolic function to predict weight loss given a specific maximum temperature and time (degree minutes) interval. They further purport that cryptocrystalline quartz specimens did not exhibit significant negative effects at temperatures below 500°C. The same was also suggested for obsidian specimens, although they state that at temperatures above 500°C obsidian experiences an increase in weight loss and surface alteration. Based on this observation, Bennett and Kunzmann (1985:8) suggest that, “Obsidian is apparently more subject to heat damage than flints.” However, they do not elaborate, nor do they provide an adequate description of the surface thermal alteration observed on the specimens, only comments in tabular form such as “dulled” and “chalky.” Apparently, no catastrophic forms of thermal alteration were observed, which does not necessarily support their assertion that obsidian is more prone to thermal alteration than cherts and flint.

A recently published combined volume focused exclusively on the thermal alteration of obsidian edited by Loyd et al. (2002) provides a wealth of information on the effects of heating on obsidian as well as the implications for obsidian hydration of thermally altered obsidian. Many researchers have demonstrated that the hydration rims of obsidian are significantly affected beginning at approximately 400°C, and become completely diminished at temperatures above 700°C (Benson 2002; Halford and Halford 2002; Origer 1996; Solomon 2002; Steffen 2002; Trembour 1979. Nakazawa (2002) has experimentally demonstrated that surface cracks and crazing begin to form on obsidian beginning at 550°C. In addition, at temperatures beyond 800°C, Steffen (2002) has recorded vesiculation, the formation of interconnected bubbles on the interior surface of obsidian, which eventually may elicited a morphological change in obsidian whereby it takes on a foam-like appearance. Bennett and Kunzmann (1985) do report that the surfaces of the obsidian specimens heated to between 500-800°C exhibited a “dulled” and “chalky” appearance. This is probably analogous to what Steffen refers to as “matte finish”, and “surface sheen” (see Steffen 2002:163 for discussion).

For the various Southwestern pottery sherds that were heated during the experiment, Bennett and Kunzmann report that ceramic material are largely unaffected by exposure to temperatures below 400°C. The authors demonstrated in the experiment that heat-induced color alteration of prehistoric ceramics occurs at temperatures above 500°C in which redware varieties can change to a darker hue, and black-on-white wares will change to a "slightly buff" color due to the oxidation of iron minerals. Furthermore, they suggest that the pigmented design on black-on-white sherds is stable under high temperature if the paint is mineral based, but may combust and fade significantly if the paint is organic based. In addition, the researchers state that at temperatures in excess of 600°C black-on-white sherds can oxidize to resemble redware, and although this was not demonstrated in their experiment and they do not provide references, other researchers have documented the process in which the color change occurs (Burgh 1950; Colten 1953; Shepard 1956). Aside from the heat-induce color alterations, the authors contend that prehistoric ceramics are structurally stable up to temperatures of 600°C since most were originally fired at temperatures lower than 600°C. The authors did not provide any references to support this assertion; however, several works exist which address firing temperatures of prehistoric ceramics (e.g., Cogswell et al. 1997; Colten 1951; Feathers et al. 1998; Goodyear 1971; Heimann and Franklin 1979; Kaiser and Lucius 1989; Rice 1987; Rye 1981; Shepard 1956; Tite 1969; Ziad and Roussan 1999). The experiment produced only one occurrence of thermal spalling on a black-on-white sherd at a maximum temperature of 500°C, and one incidence of surface cracking on a redware specimen at 600°C.

The historic materials tested by tested by the researchers included modern china, modern stoneware, enameled tinware (modern and historic), window glass and bottle glass (modern and historic). These materials were only heated to a maximum temperature of 500°C during the experiment, and minimal to no thermal alteration of was recorded by the researchers. This is not surprising since most of these materials are formed at temperatures well beyond 500°C. For example, porcelain and china ceramics are fired at temperatures of

1280-1400°C and beyond (Rice 1987). In addition, these materials are manufactured to withstand significant thermal stress since most are created for everyday use in cooking. Thermal stress in modern ceramics has received attention from several researchers in the ceramic industry (Amberg and Hartsook 1946; Buessem 1955; Chandler 1981; Coble and Kingery 1955; Crandall and Ging 1955; Davidge and Tapppin 1967; Grimshaw 1971; Kingery 1955). Glass has a melting point of approximately 700-800°C, although heating at lower temperatures may cause glass to expand and develop thermal fractures (DeHann 1997:172). For enameled tinware, the authors state that the volatilization of enamel coating occurs at temperatures above 500°C, and is thus unlikely to be significantly affected by wildland or prescribed fires.

Bennett and Kunzmann also incorporated bone into their experiment, although information regarding species and element were not provided. In addition, the researchers used "fresh" and "old" specimens in the heating trials; however, no additional information is provided regarding their categorization of fresh and old. For fresh bone specimens the authors observed charring and water loss at temperatures between 100-300°C. At temperature beyond 300°C the researchers observed that the "chemical structure of the bone is greatly altered", and becomes "chalky" in appearance (Bennett and Kunzmann 1985:12). The authors conclude that, regardless of age, the chemical structure of bone is significantly altered at temperatures above 400°C. It is unclear what the authors regard as chemical structure alteration. Bone consists of two major components, an organic phase and an inorganic phase. The organic phase (35% of dry bone mass) consists largely of protein, mostly in the form of collagen (Posner and Belts 1975). The inorganic phase is composed of mineral, mostly hydroxyapatite in microcrystalline form (Ortner et al. 1972). Several researchers have documented the processes and involved in the thermal alteration of bone (e.g., Bennett 1999; Bonucci and Graziani 1975; Bradtmiller and Buikstra 1984; Brain 1993; Buikstra ad Swegle 1989; Herrmann 1977; Kizzely 1973; McCutcheon 1992; Nicholson 1993; Shipman et al. 1984; Sillen and Hoering 1993; Stiner et al. 1995; Von Endt and Ortner 1984). Shipman et al. (1984) provide an excellent summary of the process of bone thermal alteration, which can be summarized as: 1) change in bone color; 2) change in the microscopic morphology of bone surfaces; 3) changes in the cystalline structure of bone; and 4) bone shrinkage. The degree of thermal alteration observed in bone is dependent on the temperature at which bone is exposed, the duration of exposure, position of bone in relation to heat source, bone composition, and bone size.

In addition to the electric furnace heating trials, Bennett and Kunzmann (1985) also conducted thermal shock testing of artifacts in which heated artifacts were submerged in water and assessed for damage induced by thermal shock. The authors report that cooling of submerged artifacts was precipitous, dropping from 400°C to ambient temperature of rates greater than 500°C per minute. They also concede that theses cooling rates are much greater than would be expected under field conditions during a prescribed fire. This is probably an accurate statement, with the possible exception of a scenario in which water or fire retardant is sprayed on artifacts during wildland fire suppression activities. Oppelt and Oliverius (1993) have induced thermal shock in Mesa Verde pottery sherds by applying fire retardant to sherds burned in experimental plots under controlled prescribed fire conditions. Bennett and Kunzmann report a 30% failure rate for decorated sherds and a 10% failure rated for undecorated and corrugated specimens. In addition, they also observed a 30-40% failure rate for china. The researchers did not observed thermal damage for flint/chert/chalcedony specimens, but did report a 20% failure rate for obsidian specimens. Glass specimens, window and bottle, exhibited failure rates of 70-80% and 30% respectively. This experiment suggests that inverse thermal shock can significantly damage a wide variety of archaeological material type; however, the precipitous decline in temperature achieved during the experiment is unlikely to be seen in prescribed and wildland fire scenarios, with the possible exception of instances in which fire suppression activities involving water or fire retardant and heated surface artifacts are involved. Under prescribed and wildland fire conditions, thermal stress and potential thermal shock among various artifacts types will occur due to rapid heating of artifact surfaces from ambient temperature to the maximum amount of heat energy that is conducted by the artifact from the radiant heat energy emitted by the resident flames

Bennett and Kunzmann's experiment represents the principle body of research on laboratory heating of a range of artifact classes to address the potential effects of natural fire on archaeological resources. Their research design and conceptualization of time and temperature as critical variables are innovative and remain important contributions to the fire effects literature. The major weakness of their experiment is embedded in the method used to heat artifacts. The researchers used an electric laboratory furnace to heat, which can require in excess of 30 minutes to reach a temperature of 500°C. The rate of heating in a muffle furnace is characterized by gradual and uniform temperature gradients. The specifics of Bennett and Kunzmann's heating trials are not provided in great detail, and rate of heating data are provided in terms of degree-minutes. It is apparent, however, that the researchers heated artifacts gradually over a period of several hours given the method of heating and their degree-minute calculations. The rate of heating attainable in a muffle furnace is not analogous to wildland and prescribed fire conditions where temperatures peak rapidly (within a few minutes) as the flame from passes the area in which archaeological materials are located and diminish more slowly as fuels are combusted (Chapters 2 and 4). The maximum temperatures at the soil surface, and the duration of heating generated by a natural fire are largely dependent on fuel load fire intensity and extent of combustion of fuels (Chapter 2). These conditions cannot be replicated in a laboratory setting using an electric muffle furnace. In order to address this issue, two laboratory experiments were designed:

1) Experimental heating of various artifact classes in a laboratory muffle furnace with the purpose of substantiating or rejecting the findings presented by Bennett and Kunzmann (1985). (This Chapter)

2) Laboratory wildland fire simulations in a controlled wind tunnel setting whereby various artifact classes were subjected to burning more representative of natural fire. (Chapter 4).

The details of each experimental design and results are provided in this chapter and Chapter 4.

Research Design

The laboratory heating experiment was conducted using an electric muffle furnace manufactured by Thermolyne. The experimental design consisted of ten trials beginning with a l hour 100°C trial and incrementally increasing the maximum temperature of each 1-hour trial an additional 100°C until the final trial, which achieved a maximum temperature of 1000°C. Temperature was measured using the internal thermocouple and analog display that was integral to the muffle furnace itself. Heating was controlled by setting the furnace thermostat to the desired heating trial temperature and recording the amount of time the furnace required to achieve the predetermined temperature. The muffle furnace did not accommodate an external thermocouple and data logger system; therefore, specific time and temperature curves were not generated for the experiment.

In each of the ten heating trials, 21 experimental artifacts representing a variety of artifact classes were placed in the muffle furnace for heating. In total, 210 experimental artifacts were subjected to controlled laboratory heating and analyzed for subsequent thermal alteration. Heating was initiated after the artifacts were placed in the muffle furnace, and heat up time, time at temperature, and cool down time to <100°C were recorded. Heat up and cool down time varied given the magnitude of the desired heating time temperature; however, once the predetermined temperature was established, it was maintained for 1 hour before the cool down was initiated. Prior to heating, each artifact was numbered to correspond to a specific heating trial and general descriptions of the artifacts were recorded on a data form and documented through digital photography. In addition, each artifact was measured for maximum length, width, and thickness, weighed to the nearest 1 gram using an Ohaus CS-2000 digital scale, and artifact color(s) was recorded using Munsell soil color charts (Munsell 2000). After a specific heating trial was terminated, each artifact was weighed to the nearest 1 gram to assess potential post-heating weight loss, and potential heat-induced color change was assessed using the Munsell system. In addition, artifacts were macroscopically analyzed for different forms of thermal alteration such as thermal fracturing, thermal spalling, crazing, partial combustion, and deformation. Post-heating thermal alteration of artifacts was documented on the data form and through digital photography. The descriptive artifact data in tabular form and digital photographs of artifacts pre-heating and post-heating are provided on the data CD that accompanies the dissertation (Appendix 2, Photos, Artifact Data).

Descriptions of the experimental artifacts heated during each of the ten trials of the muffle furnace experiment are provided below:

Mammal Bone Samples:

Sample 1 included sawed and sectioned appendicular elements (humerus, radius/ulna, femur, proximal and distal epiphyses and diaphyses) from domestic cattle (*Bos sp.)*. These specimens had been weathering at the soil surface in an arid environment for a period of 3 years. The cortical surfaces of these specimens were dry, cracked and flakey. These specimens were given a weathering classification of 3 on an ordinal scale of 1-3.

Sample 2 included sawed and sectioned axial elements (thoracic vertebrae spines, and rib blades) from domestic cattle (*Bos sp.*). These specimens were form a single carcass that had been weathering in the same arid environment for approximately one year. These specimens were in good condition, and were given a weathering classification of 1 on an ordinal scale of 1-3.

Sample 3 was comprised of complete domestic cattle (*Bos sp.*) teeth (mandibular and maxillary premolars and molars). These specimens were had been weathering at the soil surface in an arid environment for a period of 3 years. The enamel surfaces and root structures of these specimens were dry and cracked. The weathering classification for these specimens was recorded as 3 on an ordinal scale of 1-3.

Sample 4 included sawed and sectioned appendicular element (meta tarsal, proximal and distal epiphyses and diaphyses) from an elk (*Cervus elaphus*), which had been weathering in a mountain environment for an unknown duration, but probably over a period of less than one year. These specimens were in good condition, and given a weathering classification of 1 on an ordinal scale of 1-3.

Sample 5 included sawed and sectioned elk (*Cervus elaphus*) antler of undetermined age from a high plains environment. These specimens exhibited significant weathering, and were given a weathering classification of 3 on an ordinal scale of 1-3.

Freshwater Mussel Shell:

Large bivalve shell halves of unspecified species from Midwestern riverine environments. Each shell half was sawed into two equally sized sections. These specimens were in fair condition, and were given a weathering classification of 2 on an ordinal scale of 1-3.

Lithic Materials:

Moderate to large sized secondary flakes representing a variety of raw material types that were derived from modern flint knapping activities. Each material type is listed below:

Porcelinite (unspecified source)

Obsidian (black, red, and translucent, unspecified source)

Obsidian (black with fine gray banding, unspecified source)

Hartville Uplift chert (Hartville Uplift, Wyoming)

Pecos chert (West Texas)

Fort Hood chert (Central Texas)

Pink Bioclastic chert (unspecified source)

Phosphoria (Big Horn Mountains, Wyoming)

Novaculite (unspecified source)

Silicified Wood (East-central Colorado)

Cliff House Formation Sandstone (Mesa Verde National Park): Sawed and sectioned portions of individual sandstone blocks.

Pottery and China Sherds:

Prehistoric: Moderately sized individual black-on-white sherds from an unprovenienced collection of Southwestern specimens. The black paint on the specimens is mineral based.

Historic: Moderately sized individual decorated whiteware fragments from an historic midden area located on private property and dating from the 1920s-1950s. The painted decorations consisted of pink-red flower motifs and gold banding. Specific data regarding the manufacturer and production date were not discernable.

Glass:

Historic: Moderately sized fragments derived from an individual amber colored screw-top bottle. The specimen was obtained from an historic midden area located on private property and dating from the 1920s-1950s. Specific data regarding the manufacturer and production date were not discernable.

Trial #1 (100°C)

Heating trial number 1 was conducted at maximum temperature of 100°C for 1 hour. Heat up time to 100°C was achieved in approximately 3 minutes, and the cool down period continued for a duration of approximately 3 minutes. Post-heating macroscopic analysis of the experimental artifacts revealed no significant evidence of thermal alteration such as heat-induced color change. However, post-heating weights of bone and antler specimens revealed a 3.3-3.5% weight loss for smaller specimens, and a 5.5-5.9% loss in mass for the larger specimens. The elk antler section sustained a loss in mass of 6.5%. This suggests that internal moisture is lost, and the organic phase, primarily collagen, of bone begins to combust at temperatures as low as 100°C. The freshwater shell specimen did not exhibit a heat-induced loss in mass since it is composed primarily of calcium carbonate. In sum, the 100°C heating trial only minimally affected the organic phase of the bone and antler specimens, and had no discernable impact on the remaining artifacts. Descriptive data and a summary of artifact thermal alteration for this trial are summarized in Table 3.1.

Trial #2 (200°C)

The parameters for trial number 2 consisted of heating experimental artifacts for 1 hour at a temperature of 200°C. The heat up time required for the muffle furnace to achieve the 200°C mark was approximately 20 minutes. After the trial, the furnace required of cooling period of approximately 1 hour before the artifacts were removed for analysis.

Post-heating analysis of the experimental artifacts demonstrated that bone specimens were affected most significantly during the 200°C trial. Heat-induced weight loss associated with the combustion of the organic phase of bone ranged between 10.6-15.6% for all specimens including antler. The color of bone and antler specimens changed from white and light gray to strong brown and black post-heating giving the specimens a charred appearance. The partial combustion of the organic phase produced a light combustive residue on many of the experimental artifacts. In addition, the more heavily weathered specimens exhibited enhanced surface cracking of preexisting cracks resulting from thermal stress. The tooth specimen (mandibular third premolar) did not exhibit an observable loss in mass, but the color of the enamel changed from white to gray brown, and the root portion became blackened. The freshwater shell specimen exhibited a light gray haze over the entire upper surface, but was not affected by weight loss.

Each of the lithic and obsidian specimens exhibited a slight increase in luster. Heat-induced color change was observed for porcelinite (greenish gray to a darker greenish gray hue around the edges), Hartville Uplift chert (strong brown to strong brown with mottled red), Pecos chert (light gray to light gray with mottled weak red) pink bioclastic (pink/light gray to weak red), Fort Hood Chert (light brownish gray to reddish gray), phosphoria (dark red to dusky red), and the silicified wood specimen (strong brown/very dark gray to red). Heat induced color change in cherts from their original color to pink or red is the result of the oxidation of iron compounds to hematite, and other color changes may be attributed to the alteration of other mineralogical impurities (Luedtke 1992; Purdy 1974; Schindler et al. 1982). The novaculite specimen, however, was unaffected by heating. Flenniken and

Garrison (1975) also observed that Arkansas novaculite did not sustain heat-induced color alteration, probably due to the fact that novaculite contains very few impurities. The Cliff House Formation sandstone specimen exhibited a color change from brownish yellow to dark reddish brown haze partially due to a light combustive residue and possible heat-induced mineral alteration.

The china and pottery specimens did not exhibit any observable thermal alteration; however, the glass bottle fragment did exhibit crack propagation in an area of preexisting weakness. The results of the 200°C trial indicate that combustion of the organic phase of bone was accelerated compared to the 100°C, and that crack propagation of existing surface cracks may be enhanced. In addition, if appears that the mineral alteration of some lithic materials is initiated at 200°C. Pre- and post-heating Munsell values, thermal alteration summaries, and descriptive information for each of the experimental artifacts are provided in Table 3.2.

<u>Trial #3 (300°C)</u>

Heating trial number 3 was designed to heat experimental artifacts at 300°C for 1hr to include additional heating required during muffle furnace heat up and cool down. The muffle furnace reached the 300°C point within approximately 20 minutes, and required a cool down period of approximately 1.5 hours before the artifacts were removed.

The general observation surrounding the impact of the 300°C trial on the experimental artifacts was that all specimens exhibited a light combustive residue due to the partial combustion of the organic phase of the bone specimens. The bone specimens themselves where completely blackened giving them a charred appearance. Post-heating weight losses for all bone specimens ranged between 20-27.7%. Aside from the reduction in mass, the bone appeared to be increasingly more fragile and exhibited crack propagation of existing surface cracks as well as the combustion of a portion of the flakey surface on the heavily weathered specimens. The tooth specimen (mandibular third premolar) exhibited blackening of the enamel and the root as well as a 22.2% loss in mass. The freshwater shell exhibited a brown haze over the original pre-heat colors in addition to delamination of its interior surface and a 7.7% loss in mass.

The obsidian artifacts exhibited a more lustrous appearance post-heating, and additionally, the black and gray-banded specimen exhibited metallic-like sheen. This is what Steffen (2002:163) defines as "surface sheen", which may be caused by either organic buildup or the formation of microscopic crazing and bubbling. The chert specimens exhibited a slightly dulled appearance as well as heat-induced mineral alterations in which Hartville Uplift chert changed from strong brown to dusky red, Pecos chert was altered from light gray to reddish gray, Fort Hood chert changed from brownish gray to brown, and pink bioclastic chert was altered from pink to dark reddish gray. In addition, phosphoria was altered from its original dark red to dusky red, silicified wood was altered from strong brown/very dark gray to dusky red, and porcelinite changed from greenish gray to gray. As was recorded for the 200°C trial, the novaculite specimen did not exhibit any observable color alteration. The Cliff House Formation sandstone block section exhibited a color alteration from brownish yellow to weak red, and a loss in mass of 1.3%.

The china fragment and black-on-white prehistoric pottery sherd exhibited a slight haze resulting from the combustive residue created by the combusting organic phase in bone specimens, but were otherwise unaffected by heating to 300°C. These materials, china in particular, were fired at temperatures well beyond 300°C, thus it is unlikely that they would be significantly affected during this trial. The bottle glass fragment also exhibited a slight haze as well as the propagation of two cracks along preexisting weak points.

Overall, the results of the 300°C heating trial show an increased combustion of the organic phase in bone resulting in mass losses ranging between 20-27% combined with crack propagation for some specimens. Freshwater shell begins to delaminate on the interior surface at 300°C. Chert specimens and the silicified wood specimen exhibited clearly discernable alterations in mineralogy resulting in prominent color changes, and one obsidian specimen exhibited a characteristic heat-induced surface sheen. No thermal fracturing, spalling, or crazing was observed within the lithic sample; however it is apparent that heat-induced mineral alteration becomes prominent at 300°C. Descriptive information, Munsell values, and observed thermal alteration summaries for each of the experimental artifacts are provided in Table 3.3.

Trial #4 (400°C)

Heating to 400°C in the muffle furnace was achieved within approximately 30 minutes, and cool down to less than 100°C was accomplished over a period of approximately 1.5 hours. The experimental artifacts were heated at a constant 400°C for 1 hour in addition to the gradual heat gradient experienced during the heat-up and cool-down periods.

Post-heating analysis of the experimental artifacts showed that a moderate to heavy combustive residue was deposited on the surfaces of artifacts due to bone combustion. Bone specimens were heavily blackened and charred in appearance and exhibited mass losses between 29.4-34.5%. The antler specimen exhibited an appreciable weight loss of 37.5%. The proportion of the organic phase of bone that has been combusted has increased incrementally as heating trial temperatures have increased from 100°C to 400°C. The organic phase represents approximately 35% of the mass of dry bone (Posner and Belts 1975). Therefore, it seems reasonable to suggest that prolonged temperatures approaching the 400°C range are sufficient to combust a significant portion of the bone collagen since the bone specimens in this trial exhibited weight loss in the range of 29.4-34.5%. Other researchers have reported partial to complete combustion of the organic phase within bone at temperatures between 300-500°C (Bonucci and Graziani 1975; Kizzely 1973; Shipman et al. 1984). In addition to bone specimens, the antler section sustained a loss in mass of 37.5%. The bone specimens also exhibited crack propagation as well as thermal fractures resulting in the fragmentation of two specimens. Bone also appeared to be increasingly fragile and exhibited an overall deeply blackened color on all surfaces giving them a charred appearance. The tooth (mandibular third premolar) heated during this trial sustained a 25% loss in mass as well as an overall blackened appearance. The freshwater shell specimen exhibited a pervasive gray-brown color and significant delamination of its interior portion resulting in a flakey appearance as well as an 11.1% loss in mass.

Each of the obsidian specimens exhibited the metallic sheen recorded during the 300°C trial. The preexisting radial fracture lines, creating by the percussion of flaking, were also enhanced and slightly propagated. In addition, the black and gray-banded specimen exhibited “fine crazing”, defined by Steffen (2002:164) as very fine and shallow surface fractures that form a series of polygons. Chert specimens exhibited a dulled appearance, largely due to the combustive residue, but also experienced significant mineral alteration resulting in color changes to darker hues for porcelinite, Pecos Chert, pink bioclastic chert, and phosphoria. The color of the Hartville Uplift Chert was altered from strong brown to very dusky red, and Fort Hood Chert specimen was altered from light brownish gray to gray and dusky red. In addition the Fort Hood specimen was affected by thermal fracturing in which the proximal portion of the flake was snapped off by a uniform and linear fracture. The silicified wood flake also exhibited thermal fracturing and potlid fractures; however, in this instance thermal fracturing was pervasive and resulted in the creation of several blocky and angular fragments. In addition, this specimen experienced a significant color alteration from strong brown and very dark gray to dark red. The Cliff House Formation sandstone also exhibited a heat-induced color change from brownish yellow to weak red, as well as a loss in mass of 1.6%. The novaculite flake did not exhibit any color change or additional thermal alteration.

The combustive residue deposit observed on most artifacts also obscured the painted designs on the china fragment and the black-on-white sherd. However, no internal color alteration or thermal damage was observed on either specimen. The bottle glass fragment exhibited the black residue associated with the combustion of the organic phase of the bone specimens as well, but was also affected by thermal spalling.

The results of the 400°C indicate that significant combustion of the organic phase of bone occurs at sustained temperatures of 400°C. In addition, most bone specimens also exhibited thermal fracturing, crack propagation, and heavy blackening. For lithic specimens, the Fort Hood chert and silicified wood flakes exhibited color alteration as well as thermal fracturing, with the silicified wood specimen sustaining pervasive fracturing as well as potlid fractures. The obsidian flakes exhibited a heat-induced metallic sheen, and one specimen also showed evidence of fine surface crazing. In addition, several of the other lithic material types exhibited heat-induced color alterations resulting from mineral oxidation. These observations suggest that significant thermal alteration of lithic materials is initiated at sustained temperatures approaching 400°C. This temperature is well within the range of surface temperatures that could be expected in most prescribed and wildland fires under moderate fuel loads. The heat-up time under those conditions would of course be more precipitous with significantly diminished residence times compared to heating in a muffle furnace. Descriptive information, Munsell values, and thermal alteration summaries for each artifact are provided in Table 3.4.

Trial #5 (500°C)

Heat-up to 500°C for trial number 5 was achieved within approximately 45 minutes, 500°C was maintained for 1 hour, and the cool-down period continued thereafter for 2 hours. The combustive residue that was present on artifacts in the previous two trials (300-400°C) was not observed on any specimens heated during the 500°C trial.

It appears that the entire organic phase of the bone specimens was burned off during this trial. Post-heating weight losses for all specimens ranged between approximately 30-38%, indicating that most of the organic phase had been combusted during heating. In addition, the antler specimen sustained a 45.5% loss in mass after heating. Moreover, the bone and antler specimens were grayish brown in appearance compared to the blackened appearance of bones and antler from the 300 and 400°C trials further suggesting that collagen and other organic had been combusted. In addition to the weight loss, bone specimens exhibited thermal fracturing and crack propagation, and had become increasingly fragile. The tooth specimen (mandibular third premolar) exhibited the same grayish brown color on the root portion and a green-gray hue on the enamel portion. In addition, the enamel had deteriorated, showing evidence of crack propagation and increased brittleness as well as a loss in mass of 30%. The shell specimen also sustained a sizeable loss in mass of 25% as well as significant delamination of its interior portion and an overall change in color to green-gray.

Significant thermal alteration of lithic materials was recorded for silicified wood, Fort Hood chert, and Hartville Uplift chert specimens. The silicified wood flake exhibited pervasive thermal fracturing as well as mineral oxidation resulting in a color change from strong brown to very dusky red. Similarly, the Fort Hood chert flake also exhibited significant thermal fracturing thermal spalling, pot lid fractures, and color alteration to gray from the original light brownish gray color. The Hartville Uplift flake exhibited two potlid fractures and a color shift from strong brown to dark red. The porcelinite, phosphoria, bioclastic chert, and Pecos chert flakes also exhibited color alterations to darker hues, but no thermal fractures were observed for those specimens. Both obsidian flakes exhibited a metallic sheen and enhanced radial fracture lines, but neither showed evidence of fine crazing seen on the flake scar of the black and gray specimen from the 400°C trial. The novaculite flake did not show any discernable evidence of thermal alteration. The Cliff House Formation sandstone block section sustained a 1.2% loss in mass, and exhibited a color alteration from brownish yellow to dusky red.

The china fragment and black-on-white pottery sherd did not exhibit any observable evidence of thermal alteration. The combustive residue seen in the previous two trials was not present here. The bottle glass fragment exhibited thermal spalling and appeared to be slightly more lustrous than it was prior to heating. Although, bottle glass seems to be subject to crack propagation and thermal spalling at temperatures ranging between 200-500°C, ceramic materials (historic and prehistoric) remain stable under the same conditions.

The results of the 500°C trial indicate that bone; teeth, antler and shell are significantly impacted at this temperature resulting in combustion of the organic phase, crack propagation, and thermal fracturing. Similarly, some lithic material types such as Fort Hood chert, Hartville Uplift chert, and silicified wood are prone to thermal fracturing and strong color alteration at a sustained temperature of 500°C. Color alteration of other lithic material types as well as surface alteration of obsidian was also observed during the trial. Conversely, ceramic materials were observed to remain stable at this temperature. Munsell values, thermal alteration summaries, and descriptive information for the experimental artifacts heated during the trial are provided in Table 3.5.

Trial #6 (600°C)

The 600°C trial was conducted over a period of 4.5 hours. Experimental artifacts were placed in the muffle furnace and heating was initiated immediately thereafter. The muffle furnace required approximately 45 minutes to reach the 600°C level, which was then maintained constant for 1 hour. The cool-down period from 600°C to less than 100°C was achieved over a period of 2.5 hours.

As was recorded for the 500°C trial, there was no combustive residue present on the experimental artifacts after heating was conducted. The bone and antler specimens took on a partially calcined appearance after the trial whereby specimens were altered from their original white color to light brown-gray and dark green-gray. The organic phase of the bone specimens had been completely combusted resulting in weight loss of approximately 32-40%, and the initiation of a calcined appearance would suggest that the mineral phase was beginning to be affected by prolong heating at the 600°C level. These specimens also exhibited minor thermal fractures, crack propagation, and an overall increase in brittleness. The tooth specimen (maxillary second molar) exhibited a green-gray color alteration of the root portion and a dark green-gray color alteration of the enamel portion. In addition, the enamel sustained thermal fractures and became quite brittle as a result of heating. The post-heating weight loss recorded for the tooth was nearly 43%. The shell specimen sustained a loss in mass of 17.6% and exhibited moderate delamination of its interior surface in combination with an overall color change to green-gray.

For the lithic specimens, the Fort Hood chert and silicified wood flakes sustained the greatest degree of thermal alteration ranging from dynamic color alteration to pervasive thermal fracturing and spalling. Thermal fracturing was not observed for any of the other material types, only mineral alterations that produced significant color change for the Hartville Uplift chert (strong brown to dark red) and moderate alterations to darker hues for phosphoria, porcelinite, Pecos chert and bioclastic chert specimens. At the macroscopic level, the novaculite flake remained unaffected by heating. The two obsidian flakes exhibited a metallic sheen resulting in a more lustrous appearance, enhanced radial fracture lines, and fine crazing on some surfaces, particularly on flake scars. The Cliff House Formation sandstone block section also exhibited a color change from brownish yellow to red in addition to a 1.7% loss in mass.

The historic china fragment was unaffected by heating during this trial; however, the black-on-white prehistoric sherd exhibited a white hue, noticeably lighter than the original light gray slip, accompanied a faded appearance of the black mineral paint design. It is possible that the mineral paint and gray slip may have experienced heat induced mineral oxidation as the 600°C temperature began to exceed the original firing temperature of the ceramic. The glass bottle fragment exhibited partial melting around the edges as well as slight deformation as the trial approached the melting point of glass (soda lime), which is in the 750-870°C range (DeHann 1997:446).

In sum, the results of the 600°C trial demonstrate that the mineral phase of bone begins to be affected at this temperature and the organic phase is completely combusted. Bone, antler, and shell specimens also exhibited crack propagation, thermal fractures, and delamination (shell only). Lithic specimens experienced mineral alterations resulting in color changes ranging from complete hue change to darkened hue values. The only exception to this trend was the two obsidian specimens that exhibited fine crazing and a metallic sheen, and the novaculite flake that was unaffected by heating. The two material types that are most susceptible to heat damage are Fort Hood Chert and silicified wood, which exhibited pervasive thermal fracturing and spalling. The 600°C trial may have exceed the original firing temperature of the black-on-white sherd since it exhibited an overall lightening of the slip and black design. In addition, the glass specimen exhibited partial melting as the temperature approached the melting point of glass. Thermal alteration summaries, Munsell values, and descriptive information for each of the experimental artifacts tested are provided in Table 3.6.

Trial #7 (700°)

In order to achieve the high temperature necessary to run the trial number 7 (700°C), the muffle furnace required prolonged heat-up and cool-down intervals. In total, the trial was conducted over a period of approximately five hours. After the experimental artifacts were placed in the muffle furnace, heat-up time to 700°C was achieved over a period in excess of 1 hour. That temperature was held constant for and additional 1 hour, after which cool-down was initiated over a period of 3 hours.

The bone and antler specimens heated during this trial became calcined indicating that the organic phase had been completely combusted and that the mineral phase had been affected by heating to 700°C for a sustained period. Macroscopically, the bone specimens changed from their original white color to various shades of light blue-gray, blue-gray, and dark blue-gray as well as sustaining moderate thermal fracturing and crack propagation. In addition, the specimens became increasingly brittle upon heating, but also became increasingly hardened and rigid emitting a more high pitched percussive sound when tapped. Post-heating weight loss for bone and antlers specimens ranged between approximately 21-40%. The enamel portion of the tooth specimen deteriorated significantly due to thermal fractures and crack propagation. Additionally, the enamel was thermally altered to a blue-gray color with root section taking on a green-gray color, and heat-induced mass loss was recorded at 27%. Thermal alteration of the shell specimen was characterized by delamination, color change to an overall blue-gray hue, and a loss in mass of 20%.

Lithic specimens sustained different degrees of thermal alteration ranging from mineral alteration resulting in color changes to pervasive thermal fracturing and deterioration. The material types that were impacted most significantly were Fort Hood chert, silicified wood, and Hartville Uplift chert. In addition to significant color alterations, the Fort Hood chert and silicified wood flakes sustained severe thermal fracturing and spalling resulting in the complete deterioration of the flake. The Hartville Uplift chert flake sustained thermal fracturing as well, but not to the extent seen for the other two material types. This flake also exhibited the color change from strong brown to dark red documented in the previous trials, but in addition, the black dendrites within the material changed from black to white, perhaps due to mineral alteration. The other material types, porcelinite, bioclastic chert, and Pecos chert did not sustain catastrophic thermal alteration, but did exhibit color alterations to darker hues. The obsidian flakes exhibited a metallic sheen, enhanced radial fracture lines, and fine surface crazing on flake scars documented in previous trials. The novaculite was visually unaffected by heating to 700°C. The Cliff House Formation sandstone block section exhibited a color change from brownish yellow to weak red indicative of oxidized iron minerals as well as a loss in mass of 1.5%.

The historic china fragment was macroscopically unaffected by prolonged heating at 700°C. However, 700°C was sufficient to effectively refire the prehistoric black-on-white sherd whereby the gray slip was oxidized to very pale brown in color, and the black mineral painted design became faded. The bottle glass fragment sustained partial melting and surface deformation during the trial since 700°C is close to the melting point of glass.

The results of the 700°C trial demonstrate that the organic and mineral phases of bone are affected at this temperature resulting in a calcined blue-gray appearance, thermal fractures, crack propagation, and increased brittleness. Three lithic material types (silicified wood, Fort Hood chert, and Hartville Uplift chert) sustained catastrophic thermal damage at this temperature. The obsidian flakes exhibited fine surface crazing and a metallic surface sheen. Other lithic material types exhibited color alterations to darker hues. The slip and black mineral paint on the black-on-white pottery sherd were oxidized during the trial as well. Thermal alteration summaries, Munsell values, and general descriptive information for each of the experimental artifacts are provided in Table 3.7

Trial #8 (800°C)

After the experimental artifacts were placed in the muffle furnace, it required 1.5 hours to achieve the prescribed 800°C temperature for trial number 8. This temperature was maintained constant for 1 hour, after which the cool-down period was initiated. The muffle furnace required approximately 4 hours to cool to a temperature below 100°C. After the cool-down period, the experimental artifacts were removed from the furnace and macroscopically inspected for evidence of thermal alteration.

The immediate impact of the 800°C trial on the bone and antler specimens was a prominent color alteration from the original dull white to predominantly bright white with an admixture of very pale brown and gray giving the specimens a calcined appearance. Heat induced weight loss for these specimens ranged between approximately 32-42%, indicating that the organic phase had been completely combusted during the trial. The specimens also exhibited crack propagation, deep surface cracking, and some thermal fracturing due to thermal stress. It is likely that the mineral phase of the bone was also affected since the specimens became quite brittle and emitted a high-pitched percussive sound when tapped.

Thermal alteration of the tooth specimen was most significant for the enamel portion, which sustained pervasive thermal fractures and overall deterioration. The tooth also exhibited color alterations from white to blue-gray on the enamel and yellow to white on the root portion. The shell exhibited a color alteration form its original values to an overall pale red color, and the extent of delamination of the interior portion of the specimens was not as prominent as what had been recorded during previous trials. Heat-induced weight losses for the tooth and shell specimens where recorded as 27% and 25% respectively.

The impact of the 800°C trial on lithic materials continued the trend recorded for the previous five trials where the material types most significantly affected by heating were the Fort Hood chert, silicified wood, and Hartville Uplift chert flakes. The first two material types sustained severe thermal fracturing and deterioration that reduced the flakes to a mass of small (<5mm) individual angular fragments. This is in addition to prominent color alterations observed for both specimens. The Hartville Uplift flake also produced a significant color change from strong brown with black dendrites to dusky red with white dendrites. The flake also sustained heat-induced linear surface cracks. In addition, the pink bioclastic chert flake also exhibited linear surface cracking as well as the well-documented color alteration from pink to dark gray. The phosphoria, porcelinite, and Pecos chert flakes also sustained color alteration to darker hues; however, thermal fractures and surface cracking were not observed. The obsidian flakes exhibited a metallic sheen, enhancement of preexisting radial fracture lines, and fine surface crazing. As reported for each of the previous trials, the novaculite flake was visually unaffected by sustained heating to 800°C. Thermal alteration of the Cliff House Formation sandstone block section included a loss in mass of 1.6%, likely due to water loss, and alteration of iron minerals resulting in a color change from brownish yellow to weak red.

The thermal alteration of the manufactured china, pottery, and glass specimens ranged from minor color alteration to complete melting and deformation. The prehistoric black-on-white sherd was essentially refired whereby the slip oxidized from light gray to pink, likely due to mineral alterations, and the mineral paint became oxidized and faded. The bottle fragment melted and was completely deformed during the trial as the 800°C maximum temperature of the trial exceeded the initial melting point of glass.

The results of the 800°C trial suggest that most material types tested, with the exception of novaculite and china, are subject to observable thermal alteration at this temperature. The organic and mineral phases of bone, tooth, and antler specimens were affected during this trial, resulting in weight loss and structural alteration. Lithic materials exhibited color changes resulting from mineral alterations as well as surface cracking, severe thermal fracturing, and surface crazing for the Fort Hood chert, silicified wood, Hartville Uplift chert, pink bioclastic chert, and obsidian flakes. Other notable thermal alterations include the black-on-white pottery sherd, which exhibited mineral alterations of the slip and oxidation of the black design pigment, and the bottle glass fragment that underwent melting and subsequent deformation. The thermal alteration summaries, pre- and post-heating Munsell values, and descriptive information for each of the experimental artifacts are provided in Table 3.8.

Trial #9 (900°C)

As with the previous trials, the experimental artifacts were placed in the muffle furnace prior to the initiation of heating, and once the prescribed temperature was achieved it was maintained for 1 hour. The heat-up period for the 900°C trial required a prolonged period of approximately 1.75 hours. The cool-down period was also protracted, requiring approximately 4 hours, due to the high temperature maintained during the trial. After cooling, the artifacts were removed from the muffle furnace for evidence of thermal alteration via macroscopic analysis.

Thermal alteration of bone and antler specimens during the 900°C trial were similar to those reported for the 800°C in which specimens exhibited a chalky calcined appearance with specimens taking on a bright white hue intermixed with very pale brown. The surfaces of the bone and antler specimens also exhibited deep surface fractures and propagation of existing surface cracks as well as weight losses ranging between 35-41% for bone and 47.5% for antler. These specimens also became increasingly brittle and emitted a higher pitched percussive sound when tapped. The tooth specimen exhibited significant deterioration of the enamel, and was also color altered to hues of white and blue-gray. The root portion of the tooth was altered from its original yellow color to very pale brown, and overall the tooth exhibited a 28.6% loss in mass. Thermal alteration of the shell specimen was also similar to that reported for the previous trial in which delamination was moderate and the overall color of the interior portion of the shell changed to pale red. The post-heat weight of the shell specimen was reduced by 45%, and the specimen had become increasingly brittle.

The lithic specimens most severely impacted by heating were the Fort Hood chert and silicified wood flakes, which essentially were reduced to crumbled bits due to thermal fracturing and significantly altered in color due to mineral oxidation. In addition, the Hartville Uplift and pink bioclastic chert flakes exhibited linear surface fractures as well as color alterations to red (with white dendrites) and dark gray for each respective material type. Thermal alteration of the phosphoria flake was more pervasive for the 900°C trial compared to the previous trial in which only a color alteration to a darker hue was observed. Post-heating analysis of the phosphoria flake after this trial revealed the presence of crazing (internal fracturing), one potlid fracture, and color alteration in the form of dusky red and weak red banding. The two obsidian flakes exhibited enhanced radial fracture lines and fine surface crazing on flake scar surfaces as well as a lustrous metallic sheen. The Pecos chert flake did not exhibit evidence of thermal fracturing, only a color alteration from light gray to blue gray. The novaculite flake was visually unaffected by heating to 900°C. Thermal alteration of the Cliff House Formation sandstone included mineral oxidation resulting in a color change form brownish yellow to weak red as well as a weight loss of 2% likely attributed to water loss during heating.

Thermal alteration of the manufactured experimental artifacts varied from none for the historic china fragment to significant for the prehistoric black-on-white sherd and the bottle glass fragment. The black-on-white sherd was effectively refired as the 900°C maximum temperature probably far exceeded the original firing temperature of the vessel. Mineral oxidation of the slip was apparent in which the original gray color was altered to reddish yellow. In addition, the black mineral paint on the sherd became faded after heating. The glass bottle fragment melted and became significantly deformed as a result of sustained heating to 900°C, which exceeds the melting point of glass.

In sum, thermal alteration of the experimental artifacts heated during the 900°C was significant for the majority of material types, with the exception of the historic china fragment and the novaculite secondary flake. The organic and mineral phases of bone specimens were affected during the trial resulting in weight loss, increased brittleness, and surface fracturing. The enamel portion of the tooth specimen was severely compromised due to thermal fracturing. Lithic specimens exhibited severe thermal fracturing for the Fort Hood and silicified wood flakes as well as surface fractures, potlid fractures, and significant color shifts for the other material types. Thermal alteration of the obsidian flakes included fine surface crazing and increased luster. Other significant instances of thermal alteration include the black-on-white sherd that was oxidized to a reddish yellow color, and the bottle glass fragment that was completely deformed due to melting. Thermal alteration summaries, pre- and post-heating Munsell values, and descriptive information for each of the experimental artifacts included in the trial are provided in Table 3.9.

Trial #10 (1000°C)

The final heating trial of the experiment was trial number 10 in which a temperature of 1000°C was sustained for one hour. The muffle furnace required prolonged heat-up period of 2.5 hours to reach the prescribed 1000°C mark. Similarly, the cool-down period was protracted, requiring over 4.5 hours to return to a temperature below 100°C. In total, the combined time required to complete trial number 10 was approximately 8 hours.

After heating and cool-down, the experimental artifacts were visually analyzed for discernable evidence of thermal alteration. Thermal alteration of bone, antler, and tooth specimens was similar to that reported for the previous two trials (800°C and 900°C). These specimens exhibited a chalky calcined white and very pale brown color alteration as well as deep surface fractures, thermal fracturing, crack propagation, and weight losses ranging from 29-47%. In addition, the enamel portion of the tooth was heavily fractured and had deteriorated significantly over its pre-heated state. Thermal alteration of the shell specimen was also similar to that reported for the previous two trials in which delamination of the interior surface of the shell was moderate, and the overall color of the inner portion of the specimen was altered to pale red.

The lithic material types most significantly impacted by prolonged heating to 1000°C were the Fort Hood chert and silicified wood flakes. As recorded for the previous four trials, these flakes were severely fractured, reduced to crumbled bits, and significantly altered in color during heating. Of particular interest is the thermal alteration of the black and gray banded obsidian flake that occurred during prolonged heating to 1000°C. This flake exhibited extreme vesiculation in which the entire flake was altered to a frothy green-gray foam-like globule. Steffen (2002:164) defines vesiculation as the formation of interconnected bubbles within obsidian causing severe deformation or “puffing”. However, the author does not provide details surrounding the exact processes that are involved in vesiculation of obsidian. The other obsidian specimen used in the experiment, black, red, and translucent, did not exhibit vesiculation, only the propagation of existing radial fracture lines, fine surface crazing, and an increased luster. The Hartville Uplift flake exhibited two potlid fractures, linear surface fracturing, and mineral oxidation resulting in a color change from strong brown with black dendrites to red with white dendrites. The pink bioclastic chert specimen exhibited linear surface fractures and a color alteration from pink to dark gray. Thermal alteration of the phosphoria flake was similar to that recorded for the 900°C trial in which the original uniform dark red color was altered to weak red and dusky red banding, and crazing (non-linear web-like internal fractures) was observed. The Pecos chert flake did not exhibit thermal fractures, but was altered in color from light gray to blue-gray. As observed for each of the ten trials encompassing the experiment, the novaculite flake was visually unaffected by heating. Thermal alteration of the Cliff House Formation sandstone block section was also consist with that recorded previously whereby the mineral oxidation altered the color of the specimen from brownish yellow to weak red, and the vaporization of water contributed to a weight loss of 1.9%.

The effect of sustained heating to 1000°C on the man-made experimental artifacts was also similar to that reported for the 800°C and 900°C trials. The bottle glass fragment experienced melting resulting in severe deformation. The prehistoric black-on-white pottery sherd was effectively refired resulting in the oxidation of the slip from gray to light red and the near complete oxidation or absorption of the black mineral painted design such that is was barely visible post-heating. The historic china fragment was visually unaffected by prolonged heating to 1000°C.

The overall impact of the 1000°C heating trial on the experimental artifacts was significant. The most interesting form of thermal alteration observed during the trial was the vesiculation of the black and gray banded obsidian flake, which was transformed into a foam-like globule. Other notable instances of thermal alteration include thermal fracturing of cherts ranging from severe to minor, crazing of phosphoria, and the color alteration of all lithic material types due to mineral oxidation. The black-on-white pottery sherd was altered from black on white to essentially red buff color absent of any design. In addition, the glass bottle fragment experienced melting and was severely deformed. Bone, and antler, specimens exhibited thermal fracturing, alteration of the mineral phase, and combustion of the organic phase, which resulted in color alteration, brittleness, and weight loss. The enamel portion of the tooth specimen deteriorated severely due to thermal fracturing, and the shell specimen experienced moderate delamination, increased fragility, and color alteration of its interior surface. Thermal alteration summaries, Munsell values, and descriptive information for each artifact heated during the trial are provided in Table 3.10.

Summary and Conclusion

Thermal alteration information for each trial and artifact type is summarized in Table 3.12 at the end of the chapter. The muffle furnace experiment was conducted for three purposes: 1) to replicate similar experiments conducted by Bennett and Kunzmann (1985), and proposed but not performed by Kelly and Mayberry (1980); 2) to establish the form and extent of thermal alteration affecting a variety of common archaeological material types across differential temperature gradients ranging from 100-1000°C; 3) to provide reference data from which to assess the potential for thermal alteration of archaeological resources given a particular artifact class and maximum temperature range. The temperature range defined for the experiment is sufficient to encompass a wide variety of natural fire scenarios ranging in severity from prescribed fire in grassland fuels to prescribed and wildland fires under heavy fuel loads.

The results of the experiment show that the majority of artifact classes tested were not appreciably affected during sustained heating to 100°C. The only exception to this general trend was the initial pyrolysis of the organic phase sustained by bone specimens that resulted in reductions in pre-heated mass ranging between 3-7%. The same trend was continued during the 200°C in which the organic phase of bone began to combust, but at a greater magnitude resulting in weight losses ranging between 11-16%. In addition, the enhanced pyrolysis of collagen during this trial resulted in bone specimens that were blackened or charred in appearance. The combustive residue created by this process also adhered to the surfaces of the other experimental artifacts tested during the experiment. This residue, however, only loosely adhered to the surfaces of artifacts and is not considered a significant form of thermal alteration. The only additional form of thermal alteration observed during the 200°C trial was mineral alteration of lithic materials resulting in color changes generally characterized by shifts to darker hues. This was especially prominent for the Fort Hood chert, Hartville Uplift, and silicified wood specimens, which were altered from their original brown values to slightly darker and non-uniform red hues intermixed with the original colors. This suggests that the oxidation of iron oxides to hematite is initiated during sustained heated at 200°C. The obsidian flakes and bottle glass fragment appeared to be more lustrous in appearance post-heating and the glass specimen exhibited an enhanced linear surface crack. However, catastrophic forms of thermal alteration such as thermal fracturing and spalling were not observed during the 100°C and 200°C trials.

The 300°C and 400°C yielded more significant forms of thermal alteration across most of the experimental artifacts tested. The only exceptions to this general trend were the novaculite flake, china fragment, and pottery sherd which, upon macroscopic analysis were unaffected by sustained heating performed during these two trials. Bone specimens, however, were deeply blackened and charred in appearance due to the pyrolysis of the organic phase. This resulted in weight loss ranging between 20-35% for bone specimens as well as antler and tooth specimens. In addition, the enhancement of existing surface cracks was observed for bone and antler specimens during both trials as well as moderate thermal alteration of one bone specimens and tooth enamel during the 400°C trial. The shell specimen sustained delamination of its interior surface after heating to 400°C as well a weigh losses ranging between 8-11% after both trials. Thermal alteration of lithic materials during the 300°C was similar to that described for the 200°C trial in which mineral alterations resulted in color changes in most materials especially the Fort Hood chert, Hartville Uplift chert, and silicified wood flakes. The exception being that the color changes were more pronounced for these material types after heating to 300°C. The same general trend held constant for the 400°C; however, some specimens exhibited thermal fractures. The pink bioclastic chert flake exhibited a linear surface fracture, the Fort Hood flake sustained a complete fracture of its proximal portion, and the silicified wood flake exhibited thermal fracturing, spalling, and potlidding. This suggests that significant thermal alteration for these specific material types is initiated at 400°C. In addition, the two obsidian flakes exhibited enhanced radial fracture lines, a metallic sheen, and the black and gray banded specimen exhibited fine surface crazing. This further suggests that significant thermal alteration of obsidian is initiated at 400°C as well. The glass bottle fragment exhibited an increased luster after both trials as well as one thermal spall after heating to 400°C.

The 500°C and 600°C trials induced appreciable thermal alteration for most experimental artifacts particularly organic specimens and certain lithic material types that have been consistently affected throughout the experiment. Both the 500°C and 600°C trial produced crack enhancement, some thermal fracturing, and weight losses ranging between 34-45% for bone. However, after the 600°C bone and tooth specimens exhibited a green-gray and brown color giving them a minor calcined appearance. Thermal degradation of tooth enamel was also recorded after each trial. Delamination of the interior portion of the shell specimen also continued during both trials as did weight losses of between 18-25%. Lithic materials exhibited heat-induced mineral alterations that produced marked color changes, and thermal fracturing, spalling, and potlidding were observed for the Fort Hood chert, Hartville Uplift chert, and silicified wood specimens after both trials. The thermal alteration of the obsidian at 500°C was characterized by a metallic sheen and the propagation of radial fracture lines, and the 600°C trial produced similar results with the exception that both flakes exhibited fine surface crazing. The bottle glass fragment exhibited thermal spalling at 500°C, and slight edge melting at 600°C indicating that this temperature approaches its melting point. The black-on-white pottery sherd sustained a slight whitening of its slip, and minor fading of the black mineral paint at 600°C. The novaculite flake and china fragment were unaffected by heating during both trials.

As the temperature was increased to the 700°C and 800°C levels during the experiment thermal alteration of most material continued to follow a similar trend as reported for the previous two trials. Bone specimens exhibited a complete calcined appearance in which specimens became blue-gray and green-gray in color indicating that the hydroxyapatite is affected in this temperature range. Bone and antler specimens also exhibited surface crack propagation and some thermal fracturing was well as weight losses ranging between 21-45%. Delamination of the interior portion of shell specimens and reductions in mass of 20% continued for both trials. Tooth enamel also continued its heat-induced degradation and crack propagation observed during the previous two trials. The mineral oxidation and resulting color changes were pronounced for all material types, and the trend of significant thermal alteration of the Fort Hood chert, Hartville Uplift chert, and silicified wood flakes continued as it had during the 400-600°C trials. Obsidian flakes also continued to exhibit the propagation of radial fracture lines and fine surface crazing that had been reported for previous trials. However, the black-on-white pottery sherd exhibited color alterations of the slip from light gray to pale brown and pink during the 700°C and 800°C trials respectively, indicating the mineral oxidation had and refiring had occurred. In addition, the black mineral paint became increasingly faded after each of the trials as well. The glass bottle fragment exhibited limited melting during the 700°C and significant melting during the 800°C As recorded for the previous trials, the china fragment and novaculite flake were unaffected by sustained heating to 700°C and 800°C.

The final two heating trials generated sustained temperatures of 900°C and 1000°C respectively. The impact of the heating trials on the experimental artifacts was similar for both trials, and of greater magnitude than previous trials. Bone specimens became exhibited a chalky white and yellow calcined appearance. Specimens were noticeably more friable and exhibited a high-pitched percussive sound when tapped; indicating that the mineral phase had been altered. Bone and antler specimens also exhibited crack propagation and moderate thermal fracturing in addition to weight reductions ranging between 27-47%. Delamination of the interior portion of the shell specimen combined with significant color alteration and weight reductions of 45% were recorded during both trials. The black and gray banded obsidian flake exhibited extreme vesiculation after the 1000°C in which the flake was altered to a frothy foam-like green globule. The other obsidian flake only exhibited the linear fracture propagation and surface crazing recorded during previous trials. All lithic specimens, with exception of the novaculite flake, exhibited significant color alterations as the result of mineral oxidation. The Fort Hood chert and silicified wood flake were severely degraded to small fragmented pieces due to thermal fracturing after both trials. In addition, the Hartville Uplift and pink bioclastic chert specimens exhibited linear surface fracturing as well as potlidding for the former only. The phosphoria flake exhibited crazing (internal fracturing) during both trials and one potlid fracture after the 900°C trial. The glass specimen was completely melted during each of the trials; however, the china fragment was visually unaffected by sustained heating to high temperatures. The black-on-white pottery sherd was effectively refired during both trials resulting in significant color alterations to reddish yellow and light red. Moreover, the black pigmented design was significantly faded during the 900°C and nearly obliterated following the completion of the 1000°C.

Summaries of the thermal alteration recorded for each artifact during each of the ten heating trials are provided in Table 3.1. In sum, weathered bone (lightly and heavily) is macroscopically unaffected by heating to 100°C, but the combustion of the organic phase is initiated at this temperature since minor weight reductions of 3-7% were recorded. At 200°C combustion of collagen is enhanced and bone begins to exhibit a dark brown slightly charred appearance, and existing surface crack may be enhanced under thermal stress. Temperatures ranging between 300-500°C are sufficient to combust the majority of the organic phase of bone resulting in weight reductions of greater than 30%. This process gives bones a blackened and charred appearance in addition to potential crack propagation and thermal fracture. At temperatures between 600-700°C hydroxyapatite may be subject to thermal alteration in addition to the complete combustion of the organic phase giving bone a calcined green-gray and blue-gray appearance. Thermal alteration of the mineral phase of bone continues at temperatures ranging between 800-1000°C and bone becomes increasingly friable and chalky white and yellow in appearance. Crack propagation and thermal fracturing is also probable at this temperature range. These results are consistent with those reported by Brain (1993), Nicholson (1993), McCutcheon (1992), and Shipman et al. (1984). Each of these experimenters used variable experimental methods; however, each is roughly in agreement in their conclusions regarding the thermal alteration of bone.

Teeth are similarly affected by thermal alteration compared to bone. The specimens used during this study were significantly weathered. Previous research by Shipman et al. (1984) incorporated fresh teeth still affixed to de-fleshed mandibles. As a result, the specimens heated during the present experiment exhibited a far greater degree of crack propagation and thermal fragmentation. The thermal alteration of the root portion of teeth follow very closely the range of thermal alteration reported for bone at each respective temperature range. Weathered tooth enamel was shown to exhibit crack propagation and thermal fracture at 500°C with thermal fracturing and degradation of enamel becoming increasing severe at temperatures ranging between 600-1000°C. At high temperature the enamel becomes very friable and extremely fragmented. Tooth enamel and root sections also exhibit a blue-gray, green-gray, and white calcined appearance at temperatures between 600-1000°C.

No reference pertaining to the thermal alteration of antler has been located in the literature. However, weathered elk antler seems to follow the range of thermal alteration described. One exception would be that thermal fracturing was not observed for antler specimens, only crack propagation beginning at 200°C and consistently increasing in severity up to 1000°C. In addition, weight loss for antler was more pronounced than was recorded for bone with losses of nearly 40% for the 400-500°C trials and up to 47% for the 600-1000°C trials. Antler also exhibited a calcined appearance that is roughly analogous to that described for bone and at roughly the same temperature intervals.

Thermal alteration of shell has previously been briefly addressed Robins and Stock (1990) using campfires to address the issue of burned shell taphonomy. The study was not focused on establishing different levels of observable thermal alteration for shell at given temperatures; however, it did establish that thermally altered shell is more friable than unaltered shell. The results of the present study have shown that shell is not visually affected by sustained heating at 100°C and 200°C. Partial combustion of calcium carbonate begins at 300°C and increased incrementally as temperatures reach 1000°C resulting in mass reductions initially at 8% and culminating at 45%. The delamination of the laminar inner surface of fresh water shell and significant color alteration begins at 400°C and continues through 1000°C. As a result of heating to middle and higher temperature ranges, shell also becomes increasingly friable when handled; however, no qualitative or quantitative method was implemented to assess friability.

The two varieties of obsidian (black and gray banded, and black, red, translucent) heated during the experiment were macroscopically unaltered by sustained heating at 100°C, 200°C, 300°C with the exception of a slight increase in luster. Propagation of existing radial fracture lines and the formation of a metallic sheen were observed for both specimens beginning at 400°C and continuing for each trial thereafter until the termination of the experiment at the 1000°C trial. Fine surface crazing was consistently observed for both varieties of obsidian beginning with the 600°C and for each following trials. Vesiculation was only observed for the black and gray banded specimen during the 1000°C trial where the morphology of the flake was significantly altered from its preheated state to a green-gray, frothy, foam-like globule. Weigh losses were not recorded for either specimen during any of the trials, including the trial in which extreme vesiculation was observed.

In brief, observable thermal alteration of obsidian may potentially begin at temperatures of 400°C in the form of radial fracture line propagation, and may extend to fine surface crazing at temperatures ranging between 600-1000°C. Extreme vesiculation may occur for some varieties of obsidian at sustained heating beyond 1000°C. Surface temperatures of 400-800°C and above are possible during prescribed and wildland fires given the availability of sufficient fuel load and fire intensity. Buenger (Chapter 2) has observed fracture line propagation and fine surface crazing under field conditions during prescribed burns in heavy fuels for the black and gray banded obsidian material types used in the laboratory experiment, although vesiculation was not observed. However, Steffen (2002) has observed vesiculation of obsidian under field conditions following the Jemez fire in New Mexico. Therefore, the range of thermal alteration observed during the muffle furnace experiment is analogous to that which may be encountered in the field, and may function as a guide in estimating potential fire intensity and subsequent thermal alteration of obsidian under natural fire conditions.

The chert specimens tested during the experiment included Hartville Uplift chert, Pecos chert, Fort Hood chert, and a non-specified pink bioclastic chert. Previous research surrounding the thermal alteration of these specific material types either does not exist or was not located in the literature. The results of the experiment show that slight color changes resulting from the thermal alteration of minerals within the materials are observable beginning at 200°C. These color changes become more pronounced as the maximum temperature sustained during each trial increased up to the final temperature of 1000°C. Color alteration was most prominent for Hartville Uplift chert, which was altered for strong brown to various hues of red, probably due to the oxidation of limonite to hematite.

Significant thermal alteration of cherts in the form of thermal fracturing was first observed during the 400°C for Fort Hood chert. Thermal fracturing, spalling, and potlidding of Fort Hood chert was initiated during at 500°C and continued in severity thereafter through the final 1000°C trial where the flake was reduced to a quantity of small fragments. Fort Hood chert was clearly one of the most thermally sensitive varieties of chert tested. Second to the Fort Hood variety in susceptibility to thermal alteration was the Hartville Uplift chert, which exhibited potlid fracturing during the 500°Cand 1000°C trials was well as thermal fracturing and/or linear surface cracking between temperatures of 700-1000°C. Thermal alteration of the pink bioclastic chert was limited to linear surface cracking, which initially was observed during the 400°C trial, but was only consistently recorded for the 800-1000°C trials. Pecos chert was the most resistant to thermal alteration of the material types tested. Thermal alteration of Pecos chert was limited to color alterations from the original light gray to a darker hue of gray that increased in prominence as temperature increased. Weight losses were not observed for any of the chert specimens; however, it should be noted that the weights were coarsely obtained to only the nearest 1 gram.

The other lithic material types tested during the experiment included silicified wood, phosphoria, porcelinite, and novaculite. Silicified wood was clearly the most prone to thermal alteration of all the lithic materials used in the experiment. Prominent color alteration was observed at 200-300°C whereby the original mottled strong brown and very dark gray color was altered to red. This trend continued as the temperature of each trial increased accompanied by a progressively darker red hue. Thermal fracturing, spalling, and potlidding were initially recorded during the 400°C trial, and were especially pronounced during the 800-1000°C in which the flake was reduced to an accumulation of small fragments. The phosphoria specimen exhibited color alterations from dark red to dusky red beginning at 200°C and continuing through 1000°C. Crazing (internal fracturing) was observed for phosphoria during the 900°C and 1000°C, and minor potlid fracturing was recorded during the 900°C only. Other than alteration of its mineralogy, phosphoria seems to be rather resistant to thermal alteration up to high temperatures in the 900-1000°C. Thermal alteration of porcelinite was limited to color alterations, which were generally not prominent until the 900-1000°C trials where the original green-gray color of the material was altered to dark grey and very dark gray. No catastrophic forms of thermal alteration such as thermal fracturing or spalling were observed for porcelinite. Finally, novaculite is clearly the most resistant to thermal alteration of all the lithic material types tested. Thermal alteration of novaculite was not macroscopically observed during any of the trials, even sustained heating to 900-1000°C. This is consistent with research conducted by Flenniken and Garrison (1975), which conclude that Arkansas novaculite is very resistant to thermal alteration due to the paucity of impurities present in the material.

In sum, the thermal alteration of lithic materials is initially observable in the form of color alterations beginning at temperatures as low as 200-300°C for some material types. Significant thermal alteration of cherts (particularly Fort Hood and Hartville Uplift varieties) and silicified wood in the form of thermal fracturing and potlidding is initiated at sustained temperatures in the 400-500°C range, and may continue prevalence and severity at temperatures between 800-1000°C. Therefore, the potential for significant thermal damage to these material types under natural fire conditions is highly probably. Other lithic material types such as porcelinite, phosphoria, and novaculite are rather resistant to thermal alteration, although phosphoria did exhibit significant thermal alteration at high temperature. The results of the laboratory experiment may provide an indice from which to estimate the fire severity and fire impact where some of these materials, particularly Fort Hood chert, Hartville Uplift chert, and silicified wood, have been thermally altered under natural conditions.

The thermal alteration of the Cliff House Formation sandstone block section was limited to color alteration resulting from mineral oxidation and slight weight loss. This material type is very prevalent as an architectural masonry stone at Mesa Verde National Park. Significant thermal alteration of this material in the form of oxidation, thermal spalling, and thermal fracturing was observed during field research conducted for the present dissertation project (see Chapter 5). The gradual and sustained heating produced during the laboratory experiment is not necessarily equivalent to that produced during a wildland fire. Accordingly, no thermal spalling of fracturing was observed during the laboratory experiment; however, oxidation was observed. Oxidation of the limonite to hematite within the sandstone altered the original brownish yellow color of the sandstone to various hues of red beginning with the 200°C trial and increasing in darker Munsell values through the 1000°C trial, especially at temperatures above 500°C. These color change are consistent with an additional experiment focused on the thermal alteration of Cliff House Formation sandstone conducted for this dissertation project (see Chapter 4). Reductions in mass of between 1-2% were initiated during the 300°C and continued for each trial thereafter until the end of the experiment. These weight losses are likely the result of free water being driven from the material due to thermal stress. In sum, then, the oxidation of Cliff House Formation sandstone will initially develop at temperatures between 200-300°C, and continue in prominence at higher temperatures. Oxidation is likely to occur on this type of sandstone under most prescribed and wildland fire scenarios. The results of the laboratory experiment may also be used to gage the severity of wildland fire during post-fire inventories at Mesa Verde National Park where architectural features are impacted.

The thermal alteration of manufactured materials (historic china, glass, and prehistoric black-on-white pottery sherds) tested during the muffle furnace experiment varied depending on the material type. The Southwestern black-on-white sherds were visually unaffected by sustained heating up to 500°C, which is probably close to the original firing temperature of the vessel of this design. At 600°C, a slight color alteration of the gray slip in the form of a white haze was observed as well as minor fading of the black mineral paint used for the design. After sustained heating at 700°C, oxidation of the slip was initiated whereby its color was altered to very pale brown, and the black mineral paint became faded. This trend continued for the 800°C trial, but the slip altered in color to pink, and the design became faded. Following the 900°C trial, oxidation of the slip resulted in a reddish yellow hue as well as a faded design; and the 1000°C produced a light red slip and the near total obliteration of the black mineral painted design. Black-on-white sherd heated during the experiment were essentially refired at temperatures ranging between 700-1000°C where by the mineralogy of the slip was altered via the oxidation of iron minerals. This compares well with data reported by Burgh (1960) in which black-on-white specimens were thermally altered to red-on-buff in an electric furnace. Burgh (1960) also notes a pottery collection containing refired sherds that were burned under natural conditions in which iron contained within sherds was oxidized to yellow and red hues. The results of the present experiment suggest that oxidation of iron and subsequent color alteration occurs at temperatures ranging between 700-1000°C. This observation may potentially be used to assess fire severity of ancestral Pueblo sites burned by wildland fire if oxidized black-on-white sherds are present.

Thermal alteration of the historic glass bottle fragments consisted of an increase in luster and the propagation linear surface cracks in areas of preexisting fragility at temperatures ranging between 200-300°C. Thermal spalling along the fractured edges of the specimen was observed at temperatures of 400 and 500°C, as was an overall increase in luster. Partial melting along the fracture edges of the glass fragment was observed after sustained heating to 600°C, and melting in the form of circular surface depressions was recorded after the 700°C trial. Significant melting and deformation of glass fragments was observed during the 800-1000°C where the approximate 700-800°C melting point of glass was exceeded. Melted glass is a very consistent and reliable indicator of fire intensity due to its established melting point. Melted glass from surface contexts burned during wildland or prescribed fires would be a near certain indicator of high fire severity.

Thermal alteration of the historic china fragments used in the experiment was non-existent at all temperature thresholds (100-1000°C). Thermal alteration of china is improbable unless the temperature exceeds the original firing temperature of white-ware china (1200°C), or if sufficient thermal shock is generated by extreme fluctuations in temperature gradient. Significant thermal alteration of china during wildland and prescribed fires is unlikely, except in instances in which a specimen may have preexisting points of fragility.

The data presented above can be used as a rough guide from which to assess the potential impact of prescribed and wildland fire on archaeological resources. When assessing the impact of wildland fire on archaeological resources, this information can be used to gauge fire severity and potential maximum temperature thresholds when conducting post-fire inventories. This information may also be used to establish parameters to be incorporated into prescribed burning plans where fuel load, potential burn intensity, and the type of archaeological resource is known.

Regarding the muffle furnace experiment; however, it should be noted that heating in a laboratory muffle furnace is not necessarily analogous to the release of radiant heat energy produced by a natural fire. In Chapter 2, it was shown that surface heating during prescribed fires in wide range of fuel loads is precipitous under rather short residence times. Heating and cooling of artifacts within the muffle furnace was generally quite steady and of significant duration. Artifacts are much more susceptible to thermal shock when subjected to precipitous and intense heating that produces uneven temperature gradients within the body of the artifact. Thermal shock resulting in fracturing and spalling of lithics, sandstone, pottery, and other brittle materials has been shown to occur during sudden and precipitous temperature change, which induce differential expansion and contraction (Hettema et al. 1998; Purdy 1974; Rice 1987; Schiffer et al. 1994). Although, thermal fracturing of artifacts during the muffle furnace experiment was observed, heating during the trials was generally characterized by steady rises in temperature over a protracted period. It is likely that variables other than maximum temperature such as rate of heating are also important when addressing the potential for thermal alteration of archaeological materials under laboratory conditions. With this assumption in mind, a laboratory experiment that more closely approximated actual wildland fire conditions was developed and implemented. In addition, an experiment explicitly designed to address the thermal alteration of Cliff House Formation Sandstone was also conducted. The specifics of these experiments and the results are provided in Chapter 4.

Table (3.1) Muffle Furnace Artifact Heating Experiment: Thermal Alteration Summary

Temp °C Artifact	100°	200°	300°	400°	500°	600°	700°	800°	900°	1000°
H. weath. Bone (*Bos*)	WL 5-6%	WL 11% CC(3) CH	WL 27% CC(3) CH CRE(1)	WL 33% CC(3) CH CRE(1) FR(1)	WL 34% CC(2) CRE(1)	WL 36% CC(2) CL CRE(1)	WL 37% CC(2) CL CRE(2)	WL 37% CC(2) CL CRE(2)	WL 38% CC(2) CL CRE(3)	WL 38% CC(2) CL CRE(3)
Lt. weath. Bone (*Bos*)	WL 3%	WL 15% CC(3) CH	WL 22% CC(3) CH CRE(1)	WL 35% CC(3) CH CRE(1)	WL 45% CC(2) CRE(1)	WL 39% CC(2) CL CRE(1)	WL 21% CC(2) CL CRE(2)	WL 42% CC(2) CL CRE(2)	WL 39% CC(2) CL CRE(2)	WL 36% CC(2) CL CRE(2)
Lt. weath. Bone (*Cervus*)	WL 4%	WL 16% CC(3) CH CRE(1)	WL 20% CC(3) CH CRE(2)	WL 29% CC(3) CH CRE(2) FR(3)	WL 29% CC(2) CRE(2) FR(2)	WL 38% CC(2) CL CRE(2)	WL 30% CC(2) CL CRE(2) FR(2)	WL 32% CC(2) CL CRE(2) FR(2)	WL 32% CC(2) CL CRE(2) FR(2)	WL 35% CC(2) CL CRE(2) FR(2)
Tooth (*Bos*)	None	CC(3) CH	WL 22% CC(3) CH	WL 25% CC(3) CH	WL 30% CC(2) FR(1)	WL 42% CC(2) CL FR(2)	WL 27% CC(2) CL FR(2)	WL 27% CC(2) CL FR(3)	WL 27% CC(2) CL FR(2)	WL 30% CC(3) CL FR(3)
Antler (*Cervus*)	WL 7%	WL 11% CC(3) CH CRE(1)	WL 28% CC(3) CH CRE(1)	WL 38% CC(3) CH CRE(2)	WL 39% CC(2) CRE(2)	WL 43% CC(2) CRE(2)	WL 45% CC(2) CL CRE(2)	WL 42% CC(2) CL CRE(2)	WL 38% CC(3) CL CRE(2)	WL 47% CC(3) CL CRE(2)
Shell (unspec.)	None	CC(1)	WL 8% CC(1)	WL 11% CC(3) DL(2)	**WL 25%** CC(2) DL(2)	WL 18% CC(1) DL(1)	WL 20% CC(2) DL(2)	WL 20% CC(3) DL(1)	WL 45% CC(3) DL(2)	WL 45% CC(3) DL(2)
Obsidian (blk/gry)	None	>L	>L	MS CRE(1) SCZ(1)	MS CRE(1)	MS CRE(1) SCZ(1)	MS CRE(1) SCZ(1)	MS CRE(2) SCZ(1)	MS CRE(2) SCZ(2)	MS VS(3) CRE(2) SCZ(2)
Obsidian (bk/rd/cl)	None	>L	>L	MS CRE(1)	MS CRE(1)	MS CRE(1) SCZ(1)	MS CRE(1) SCZ(1)	MS CRE(2) SCZ(1)	MS CRE(2) SCZ(1)	MS CRE(2) SCZ(1)
Porcelnite (grn-gry)	None	MCC (1)	MCC (1)	MCC (1)	MCC (1)	MCC (1)	MCC (1)	MCC (2)	MCC (3)	MCC (3)
Chert Hartville (strg. brwn)	None	MCC (2)	MCC (2)	MCC (2)	MCC (3) PL	MCC (3)	MCC (3) FR(2)	MCC (3) LFR(1)	MCC (3) LFR(1) FR(1)	MCC (3) PL FR(1)

Table (3.1) Muffle Furnace Artifact Heating Experiment: Thermal Alteration Summary (cont.)

Temp. °C Artifact	100°	200°	300°	400°C	500°	600°C	700°	800°	900°	1000°
Chert Pecos (light gry)	None	MCC (1)	MCC (1)	MCC (1)	MCC (3)	MCC (3)	MCC (3)	MCC (3)	MCC (3)	MCC (3)
Chert Fort Hood (brwngry)	None	MCC (2)	MCC (2)	MCC (3) FR(1)	MCC (3) FR(2) SP(2) PL	MCC (3) FR(2) SP(2) PL	MCC (3) FR(2) SP(3) PL	MCC (3) FR(3) SP(3)	MCC (3) FR(3) SP(3)	MCC (3) FR(3) SP(3)
Chert Bioclastic (pink)	None	MCC (1)	MCC (1)	MCC (1) LFR	MCC (3)	MCC (3)	MCC (3)	MCC (3) LFR(1)	MCC (3) LFR(1)	MCC (3) LFR(2)
Phosphoria (dark red)	None	MCC (1)	MCC (1)	MCC (2)	MCC (3)	MCC (3)	MCC (3)	MCC (3)	MCC (3) ICZ(1) PL	MCC (3) ICZ(3)
Novaculite (wht/pink)	None	None	None	None	None	None	None	None	None	None
Silic. Wood (brwn/gry)	None	MCC (2)	MCC (3)	MCC (3) FR(3) SP(2) PL	MCC (3) FR(2)	MCC (3)	MCC (3) FR(2)	MCC (3) FR(1) SP(3) PL	MCC (3) FR(3) SP(3) PL	MCC (3) FR(3) SP(3)
Sandstone Cliff House (yell/brwn)	None	MCC (1)	WL 1% MCC (1)	WL 2% MCC (2)	WL 1% MCC (3)	WL 2% MCC (3)	WL 2% MCC (3)	WL 2% MCC (3)	WL 2% MCC (3)	WL 2% MCC (3)
China Wht.Ware (decorated)	None	None	None	None	None	None	None	None	None	None
B/W sherd (gry/blk)	None	None	None	None	None	CC(1) PF(1)	CC(2) PF(2)	CC(2) PF(2)	CC(3) PF(2)	CC(3) PF(3)
Bottle Glass (amber)	None	LFR(1) >L	LFR >L	SP(1) >L	SP(1) >L	>L MLT(1)	>L MLT(1)	>L MLT(3)	>L MLT(3)	>L MLT(3)

THERMAL ALTERATION CODES:

CC (1,2,3) = Thermally-induced color change (1=light, 2=moderate, 3=heavy)
CH = Charred appearance derived from combustion of the organic phase of bone specimens
CL = Calcined (bone specimens only)
WL% = Thermally-induced weight loss (% loss based on pre-heat specimen weight)
CRE (1,2,3) = Thermally-induced enhancement of preexisting surface cracks (1=light, 2=moderate, 3=heavy)
DL (1,2,3) = Thermally-induced delamination of the interior portion of shell specimens (1=light, 2=moderate, 3=heavy)

FR (1,2,3) = Thermal fracturing (1=light, 2=moderate, 3=heavy)
SP = **(1,2,3)** Thermal spalling (1=light, 2=moderate, 3=heavy)
PL = Potlid fracture (lithic specimens only)
LFR = Linear surface fracture (1=light, 2=moderate, 3=heavy)
MCC (1,2,3) = Thermally-induced mineral alteration resulting in a color change (1=light, 2=moderate, 3=heavy)
MS = Metallic sheen (obsidian specimens only)
SCZ (1,2,3) = Fine surface crazing (obsidian specimens only)(non-linear) (1=light, 2=moderate, 3=heavy)
VS = Vesiculation, surface bubbling resulting in puffed, foam-like appearance in obsidian (1=light, 2=moderate, 3=heavy)
ICZ (1,2,3) = Crazing derived from internal thermal fracturing (non-linear, web-like) (1=light, 2=moderate, 3=heavy)
>L = Increase in luster
<L = Decrease in luster
PF (1,2,3) = Thermally-induced paint fading (1=light, 2=moderate, 3=heavy)
MLT = Melting and related deformation (1=light, 2=moderate, 3=heavy)
None = No visual evidence of thermal alteration

CHAPTER 4

LABORATORY WILDLAND FIRE SIMULATION AND THE EFFECTS OF HEATING ON ARCHAEOLOGICAL MATERIALS

Introduction

Previous research involving laboratory wildland fire simulation to address the impact of fire on archaeological resources is nonexistent. Laboratory research performed by archaeologists explicitly focused on addressing the potential for thermal alteration of archaeological materials during natural fire has generally been limited to the heating of experimental artifacts within electric laboratory furnaces (Bennett and Kunzmann 1985; Burgh 1960; Steffen 2002; see also Chapter 3). While heating in an a muffle furnace is an expedient method from which to observe the range of thermal alteration for various artifact classes given a specific temperature, it is quite limited in its approximation of the conditions archaeological materials would experience during a wildland fire. Heating in a muffle furnace is generally gradual and uniform whereas soil surface heating during natural can potentially be rather precipitous and severe (Chapter 2). The potential for significant thermal alteration of archaeological materials during a wildland or prescribed fire is likely to be much greater than that experienced by heating in an electric furnace due to the likelihood of significant and differential heating that could induce thermal shock and significant thermal alteration of artifacts.

In order to address this issue, a research design explicitly focused on replicating wildland fire conditions where archaeological materials are also incorporating into the fire simulations was developed and implemented. Laboratory wildland fire simulations were conducted at the USDA Forest Service Intermountain Fire Sciences Laboratory (IFSL) in

Missoula, Montana. The research project was a collaborative effort performed with the assistance and direction of members of the IFSL staff (Jim Reardon, Kevin Ryan, and staff). The wildland fire simulations are based on mathematical fire behavior models developed by Rothermel (1972) and Albini (1976). The IFSL staff and others have developed accurate and replicable methods to simulate wildland fire conditions in the laboratory which have been used to address several issues regarding wildland fire behavior (Rothermel and Anderson 1966; Catchpole et al. 1998; Catchpole et al. 1993).

The research objectives of this project included: 1) Simulation of variable fuel loads and wildland fire intensities in a controlled laboratory environment; 2) The incorporation of experimental artifacts, representative of a range of artifact classes, into the fire simulations with the purpose of assessing potential thermal alteration given a specific artifact type, fuel load, and fire intensity; 3) From the time/temperature curves and time/heat flux data generated during the simulations, establish the temperature and heat flux ranges at which significant thermal alteration of a specific artifact type occurs; 4) Utilize these data to make predictions regarding the potential for thermal alteration of archaeological resources under actual field conditions given a specific artifact class, fuel load, and wildland fire burn intensity.

In addition to the primary experiment, two secondary experiments were conducted to address specific issues regarding the potential for wildland fire to confound accurate thermoluminescence (TL) dating of pottery sherds, and to more thoroughly document the thermal alteration of Cliff House Formation Sandstone. The TL dating experiment was run in conjunction with the primary IFSL experiment. The secondary sandstone thermal alteration experiment was run independent of the main experiment. The research methods and results of each of the respective experiments are provided in the artifact section of this chapter.

The fundamental basics surrounding the significant thermal alteration of archaeological materials such as thermal cracking, spalling, and fracturing involve:

1. Interaction between the heat source (fire) and a heat sink (artifact).
2. The amount of energy released by combusting fuels which is dependent on fuel load and rate and duration of burning.
3. The amount of energy absorbed by the artifact which is a function of energy and the thermal conductivity of the artifact.
4. The temperature range and length of time an artifact is heated during burning.
5. The compositional structure and thermal properties of an artifact to include important variables such as coefficient of thermal expansion, thermal conductivity, and tensile strength.

Research Design

Laboratory wildland fire simulations were performed in a large combustion chamber within an environmentally controlled wind tunnel. Through the use of a computer-automated system, wind velocity, relative humidity, and ambient temperature within the chamber can be precisely controlled. The combustion chamber measures approximately 3mW x 3mH x 12mL and is constructed of steel panels with fire resistant windows that permit fire behavior observations (see Anderson and Rothermel 1965; Rothermel and Anderson 1966 for description). Wildland fire simulations were conducted on a burn table positioned within the wind chamber (Figure 4.1). The burn table was divided into two sections, the fuel bed measuring 88 x 186cm, and the sediment bed, which measures 88 x 45cm where the experimental artifacts were placed (Figure 4.2). Excelsior (*Populus tranulos)* and ponderosa pine (Pinus *ponderosa)* sticks used as fuel during the simulations. The primary fuel source was excelsior, which consists of variable length strands of wood that are stripped from poplar stock (~2.5 x 0.8 mm in cross-section) (also referred to as wood wool). The ponderosa sticks are machined (6mm in cross-section) lengths (~1m) of wood that resemble lengths of doweling. Fuel loading was established by placing predetermined g/m^2 distributions/packing ratios (mass per unit area) of excelsior on the fuel bed prior to ignition. The fuel-packing ratio represents the fuel volume per unit volume of the fuel bed. The defined g/m^2 packing ratios of excelsior and ponderosa sticks formulaically correlate to standardized ton/acre fuel loads that characterize combustible fuels common to natural environments (Anderson 1982; Schuette 1965). For the majority of the experiment shredded excelsior was placed in the fuel bed only, not overlain on the sediment bed and experimental artifacts in order to produce an oxidizing environment in which radiant heat energy exposure on the artifacts was optimized. However, two sets of simulations were conducted where shredded excelsior fuels were placed on the sediment bed and experimental artifacts in order to simulate a reducing environment similar to field conditions where duff and light litter overlay artifacts deposited on the mineral soil surface. In addition, the Moderate fuel treatment consisted of cribbed fuels where stacked pine sticks were used in place of shredded excelsior. Ignition of excelsior fuels was achieved using a linear deposit of alcohol on the leading edge of the fuel bed and an electric coil operated from the exterior of the wind tunnel. Large fraction Brule Formation clay provided the sediment for the artifact bed. Data on flame height, length, and angle were recorded by video taping flaming combustion during each trial, and using a calibrated measurement system post-fire during video play-back (McMahon et al. 1986) (note that flame angle is measured such that 0° is vertical and 90° is horizontal).

For the experiment we simulated 4 different fuel loads representative of a wide range fuel models found in natural environments common to the Western United States; Heavy, Moderate, Moderate-Light, and Light. Brief descriptions of each of the standardized fuel loads used in the experiment are provided below:

1) Heavy (1947 g/m^2 excelsior/sticks) or (8.76 ton/acre) (3191.02 kg/ha). This fuel loading is roughly analogous to a mixed conifer environment with light ground fuels (Anderson 1982).

2) Moderate (1421 g/m^2 excelsior/sticks) or (6.33 ton/acre) (2329.77 kg/ha). This fuel loading is roughly analogous to an open piñon-juniper environment with light understory (Anderson 1982).

3) Moderate-Light (973 g/m^2 excelsior/sticks) or (4.34 ton/acre) (1597.35 kg/ha). This fuel loading is roughly analogous to an open sagebrush environment or an open ponderosa environment with grass understory (Anderson 1982).

4) Light (225 g/m^2 excelsior/sticks) or (1.00 ton/acre) (368.05 kg/ha). This fuel loading is roughly analogous to a grassland environment (Anderson 1982).

In addition, we also incorporated two different wind velocities into the experiment to add variable fire intensities for each of the four fuel load treatments.

1) High Wind Velocity (512-525 ft/min, ~5-6 mph) (156-160 m/min, ~8-9.6 kph)

2) Low Wind Velocity (256-265 ft/min, ~2-3 mph) (78-80 m/min, ~3.2-4.8 kph)

Wind velocity was measured at the sediment bed within the wind chamber using computer automated environmental controls. It should be noted that wind velocity measured at the sediment surface correlates to substantially greater atmospheric 20ft wind velocities encountered during actual wildland fires.

The combination of variable wind velocity, differential fuel loads, and fuel placement (fuel absent on artifacts or fuel present on artifacts) produced a total of 10 experimental conditions. Each experimental condition was performed and then replicated 2 times with the exception of the light fuel load conditions that were run only once with no replication. In total, the experiment consisted of 26 trials as each fuel loading and wind velocity condition and associated replicate was introduced over the duration of the experiment. Summaries of each fuel load / wind velocity condition and associated trials are provided below.

Trials #1-3 (8.64 ton/acre fuel load, 5-6 mph wind velocity)

Trials #4-6 (6.33 ton/acre fuel load, 5-6 mph wind velocity)

Trials #7-9 (4.34 ton/acre fuel load, 5-6 mph wind velocity)

Trial #26 (1.00 ton/acre fuel load, 5-6 mph wind velocity)

Trials #13-15 (8.64 ton/acre fuel load, 2-3 mph wind velocity)

Trials #16-18 (6.33 ton/acre fuel load, 2-3 mph wind velocity)

Trials #10-12 (4.34 ton/acre fuel load, 2-3 mph wind velocity)

Trials #22-24 (Fuel on Artifacts) (4.34 ton/acre fuel load, 2-3 mph wind velocity)

Trial #25 (1.00 ton/acre fuel load, 2-3 mph wind velocity)

Trials #19-21 (Fuels on Artifacts) (8.64 ton/acre fuel load, 2-3 mph wind velocity.)

Prior to the ignition of fuels during each fire simulation, experimental artifacts were placed on the sediment bed, and thermocouples were positioned on the upper and lower surfaces of each artifact to record the temperature differential between the upper and lower surfaces of artifacts during burning. The position of the artifact and its associated pair of thermocouple was held constant throughout the experiment. Temperature data was recorded using 22 thermocouples wired to three Campbell Scientific Inc. CR10 data loggers that were programmed to record temperature in °C every 1 second. Thermocouples were placed on the upper and lower surfaces of artifacts in order to assess the temperature differential between these two surfaces during burning since thermal fracturing of brittle materials is generally the result of compressive and tensile thermal stress generated by uneven heating. In addition, heat flux data in the form of Total Flux (convection and radiant combined) and Radiant Flux (radiant only) were recorded in kw/m^2 using two Medtherm radiometers; one positioned at the surface of the sediment bed to measure soil heat flux, and one positioned 25cm above the sediment bed to measure air heat flux (Figure 4.3).

The experimental artifacts burned during each trial of the experiment, and their position on the sediment bed relative to the terminal end of the fuel bed, are summarized below:

1. Corrugated Pottery Sherd (unprovenienced Southwestern sherd) (35cm from fuels)
2. Black-on-White Pottery Sherd (unprovenienced Southwestern sherd) (15cm from fuels)
3. Black Hills Quartzite Primary Flake (modern replicate) (13cm from fuels)
4. Hartville Uplift Chert "Core" (nodule, roughly the sized of an exhausted core) (10cm from fuels)
5. Pecos Chert Biface and Fort Hood Chert Biface (modern replicate, fragmented unfinished Paleo-Indian points)(30cm from fuels).
6. Obsidian Biface and Blade (black/red/translucent and black/gray-banded unknown sources)(modern replicates)(34cm from fuels)
7. Glass (modern bottle fragments, clear and amber) (30cm from fuels)
8. Freshwater Mussel Shell (small and large, unspecified species) (20cm from fuels)
9. Elk (*Cervus*) Antler (sawed into sections) (30cm from fuels)
10. Domestic Cattle (*Bos)*, Elk (*Cervus*), and Deer (*Odocoilius*) Bone (appendicular elements sawed sections) (16cm from fuels)
11. Cliff House Formation sandstone (block sections) (38cm from fuels)

In total, 286 experimental artifacts were subjected to burning during the 26 wildland fire simulations that comprised the overall experiment. Descriptive data for the experimental artifacts was collected prior to burning and post-burning. Artifacts were measured for maximum length, width, and thickness, weighed to the nearest .01 of a gram using a digital scale, and assigned Munsell color values. Artifacts were also photographed using a digital camera prior to each simulation and again following burning (see Appendix 3, Photos, on Data CD). Thermal alteration of artifacts was assessed by macroscopic analysis following each simulation and recorded by notation. Figures 4.4 and 4.5 illustrate pre-burn and post-burn (heavy fuel trial) conditions of experimental artifacts. (Descriptive artifact data and thermal alteration analysis coding of artifacts are summarized in Appendix 3, Table 4.1 (Contained within the data CD accompanying the dissertation).

Heavy Fuel Load / High Wind Velocity Condition (Trials #1-3)

<u>Trial #1</u>

The first series of fire simulations were performed using the heavy fuel load (8.67 ton/acre) (3191.02 kg/ha) paired with the high wind velocity treatment. Three trials were conducted under this experimental treatment using the methodology outlined in the previous section. Trial #1 produced maximum flames lengths of .77m, flame heights of .54m, and a flame angle of 45.5°. The peak temperatures recorded on the upper surfaces of the experimental artifacts ranged between 814.0-401.0°C, with most falling within the 500-600°C range. Peak upper surface temperatures were sustained for 13-42 seconds with the exception of the 814°C reading, which was sustained for only 1 second. Maximum temperatures recorded on the lower surfaces of artifacts ranged between 480-39°C. The

480°C reading is anomalous and may have recorded due to the presence of an open space between the artifact and the sediment surface in which the release of radiant heat energy was greater. The majority of maximum temperatures recorded on the lower surfaces of artifacts were in the 100-200°C range. The time/temperature curves generated for Trial #1 show that the upper surfaces of artifacts experienced precipitous heating in which temperatures peaked within 30-90 seconds (Appendix 3, Figure 4.6, data CD). In contrast, time and temperature curves generated from thermocouples positioned at the lower surfaces of artifacts were less severe and more protracted. Peak soil flux readings at the soil surface were 27.86 kw/m^2 for Radiant Flux and 57.18 kw/m^2 for Total Flux, and 30.41-67.64 kw/m^2 for Radiant and Total Air Flux respectively (Appendix 3, Figure 4.7, data CD).

Observable thermal alteration of the experimental artifacts ranged from a combustive residue deposit present on the exposed surfaces of all specimens, to thermal fracturing for some artifacts, particularly lithics. All specimens were blackened with a soot deposit loosely adhering to the upper surfaces of artifacts as well as a blackish tar deposit that resiliently adhered to artifacts. These deposits are the byproducts of the combustion of organic fuels (excelsior). The tar deposit is a condensate tar produced by combusting fuels, which condenses on the cooler surfaces (artifacts) located below the fire (Yokelson et al. 1997). The soot deposit is easily removed from artifact surfaces; however, the tar deposit adheres to artifacts more tenaciously requiring vigorous scrubbing with a pumice based hand soap and brush. Significant thermal alteration in the form of thermal fracturing was observed for the quartzite flake, which was fragmented into three pieces. The flake also exhibited mineral oxidation resulting in a color change from brown to reddish brown along the margin of the fracture surface. Peak upper and lower surface temperatures recorded for this specimen were 551.2-252.3°C respectively. In addition, the chert core sustained one thermal spall as well as two linear surface cracks across the entire upper surface of the specimen. Maximum upper and lower surface temperatures recorded for the chert core were 559.1-190.8°C. The obsidian biface exhibited the propagation of preexisting radial fracture lines and surface crazing under maximum temperature of 814-480.6°C for upper and lower surfaces. The sandstone block section exhibited light mineral oxidation traversing the leading edge of the specimen resulting in a thin linear streak of red color alteration. Bone and antler specimens exhibited charring and partial combustion resulting in weight losses ranging between.3.4-6.0%. Thermal alteration of the shell specimen took the form of delamination of the inner surface of the shell as well as a loss in mass of 0.83%. Peak upper surface temperatures recorded for organic specimens ranged between 455.1-643.9°C. All organic specimens were noticeably more friable during handling post-fire.

Trial #2

The second trial under the heavy fuel load / high wind velocity treatment was performed as a replicate. Flame measurements showed maximum flame lengths of 0.76m, heights of 0.47m, and a flame angle of 54.7°C. Maximum temperatures recorded by thermocouples positioned on the upper surfaces of artifacts ranged between 888-392.1°C, and those placed beneath artifacts recorded peak temperatures of 595.1-84.9°C. The 595.1°C reading is anomalous and was likely registered as flames or significant levels of heat energy advanced beneath the artifact due to a gap between the artifact and sediment bed. The 888°C reading was maintained for a brief period for one thermo couple only. The majorities of upper surface maximum temperatures fell within the 500-700°C range, and were sustained for approximately 25-82 seconds. The ascension from ambient temperature to maximum upper surface temperature was rapid, generally peaking within 30-60 seconds. Conversely, lower surface temperatures reached lower maximums over a more protracted period of 2-3 minutes. Time and temperature curves for Trial #2 are provided in (Appendix 3, Figure 4.8, Data CD). Heat Flux readings were 43.48-20.32 kw/m^2 for Total and Radiant Soil Flux, and 60.81-24.45 kw/m^2 respectively for Total and Radiant Air Flux (Appendix 3, Figure 4.9, data CD).

Thermal alteration of experimental artifacts was similar to that observed during Trial #1. All artifacts exhibited heavy soot and combustive tar on exposed surfaces producing a deeply blackened appearance. Significant thermal alteration induced by thermal shock was observed for the quartzite flake and Pecos chert biface. The quartzite specimen sustained thermal fractures (4 fragments) at the distal end of the flake where the material was thinnest. Peak upper and lower surface temperatures recorded for this specimen were 650.3-595.1°C. The Pecos chert biface sustained a complete fracture at its midpoint, essentially fragmenting the specimen into halves. This occurred under a rather severe differential between maximum upper and lower surface temperatures, which were 813.0-349.0°C respectively. The chert core exhibited one thermal spall on its upper surface, which was associated with a peak upper surface temperature reading of 576.2°C. Thermal fracturing was also observed for the glass specimen (historic canning jar fragment), which was fractured into 22 pieces under extremely differential upper and lower peak surface temperatures of 888.0-65.8°C. The obsidian biface exhibited the propagation of preexisting linear fractures lines under peak upper and lower surface temperatures of 624.4°C and 187.3°C. The sandstone specimen exhibited faint oxidation along the upper edge of the leading surface (linear reddening). Bone and antler specimens were deeply charred and sustained partial combustion of the organic phase resulting in reductions in mass of 5.4-9.1%. In addition, the bone specimen (weathered *Bos* tibia section) sustained noticeable enhancement of preexisting surface cracks. Peak upper surface temperatures associated with bone and antler specimens ranged between 692.1-

613.7°C. Under similar conditions, the shell specimen sustained interior surface delamination and a 4.1% reduction in mass. The friability of all organic specimens was enhanced post-heating.

Trial #3

The heavy fuel load / high wind velocity treatment was replicated an additional time during Trial #3, and then terminated. Flame data derived from video analysis showed that the simulation generated maximum flame lengths of 0.76m, heights of 0.43m, and flame angles in the 55.4°C range. Peak temperatures recorded on the upper surfaces of artifacts ranged between 835.0-300.6°C with the majority of maximum temperatures reaching the 500-700°C mark. Residence time for peak and near-peak upper surface temperatures range between 20-75 seconds, and heat-up time from ambient to peak temperature was precipitous, generally occurring within 30-75 seconds. Maximum lower surface temperature ranged between 445.4-54.1°C, and similar to that reported for the previous two trials, the 445.4°C is anomalous. Time/temperature curves for upper surface thermocouples rise and fall sharply, while the lower surface curves are more protracted indicating less severe heating gradients. The temperature differential between peak upper and lower artifact surfaces was generally greater than 50% indicating the potential for significant levels of thermal stress within the experimental artifacts. Peak heat flux readings from the sediment surface were 51.2 kw/m^2 for Total Flux and 16.8 kw/m^2 for Radiant Flux, and those recorded 25cm above the sediment surface were 60.9 kw/m^2 for Total Flux and 19.8 kw/m^2 for Radiant Flux. Graphical representations of time/temperature and heat flux/time curves are provided in Appendix 3, Figure 4.10 and Figure 4.11, Data CD.

Thermal alteration of experimental artifacts during trial #3 was similar to that reported for artifacts from the previous two trials. Every artifact exhibited soot and combustive residue deposits on exposed surfaces. Significant forms of thermal alteration were observed for two lithic specimens and the glass specimen. The quartzite flake sustained thermal fractures near the distal end of the flake where it was thinnest. Mineral alteration resulting in color change from brown to reddish brown was also observed on two of three fragments. This specimen experienced a peak upper surface temperature of 613.5°C and a peak lower surface temperature of 321.4°C. The Hartville Uplift chert core exhibited extensive thermal fracturing of the thin portion of the nodule resulting in 22 individual fragments. Mineral alteration resulting in color change from yellowish brown to dusky red was also observed on 19 the fragments. Peak upper and lower surface temperatures for this specimen were 630.9-404.4°C. In addition, one potlid fracture was also observed on one of the fragments. The glass specimen (historic canning jar fragment) exhibited significant thermal fracturing that resulted in fragmentation into 15 pieces. Thermal alteration of bone and antler consisted of charring and partial combustion resulting in reductions in pre-burn mass of 5-7% as well as the enhancement of pre-burn surface cracks on the weathered on the weathered *Bos* specimen. The freshwater shell specimen also sustained a weight loss of approximately 4% as well as delamination of the inner surface. Organic specimens were noticeably more friable during handling post-burn. The sandstone block section exhibited light oxidation in the form of linear reddening along the leading edge of the specimen where the associated maximum upper surface temperature 300.6°C.

Moderate Fuel Load / High Wind Velocity Condition (Trials #4-6)

The second round of fire simulations were performed using the same high wind velocity defined for the previous three trials; however, the fuel treatment was reduced to 6.33 ton/acre (2329.77 kg/ha) to simulate a moderate fuel load. In addition, cribbed excelsior dowels were used in place of shredded excelsior to produce the desired fuel loading. Three trials were conducted under this experimental condition using the methodology outlined in the research design section.

Trial #4

Flaming combustion during Trial #4 produced maximum flame lengths of 1.2m, heights of 0.73m, and an angle of 52.1°C. The cribbed fuels produced longer flame lengths compared to the shredded excelsior fuels used in the previous three trials. Peak heat flux measurements were 49.6 kw/m^2 for total flux at the soil surface, 18.6 kw/m^2 for soil radiant soil flux, 59.4 kw/m^2 for total heat flux 25cm above the sediment surface, and 19.6 kw/m^2 for radiant air flux. Peak temperatures recorded on the upper surfaces of artifacts ranged between 649.7-368.1°C, with the majority of recorded maximums ranging between 400-500°C. Maximum upper surface temperatures peaked within 30-70 seconds and were sustained at high levels for 15-22 seconds. Peak temperatures from thermocouples placed on the lower surfaces of artifacts ranged between 382.1-102.7°C, the majority of which registered between 100-200°C. Lower surface temperatures peaked and fell more gradually and uniformly compared to peak upper surface temperatures in which curves were serrated and precipitous. Time/temperature and heat flux curves are summarized graphically in Appendix 3, Figure 4.12 and Figure 4.13, data CD.

Thermal alteration of experimental artifacts consisted of soot and combustive residue deposits on the exposed surfaces of each specimen burned during the trial. Significant thermal alteration of experimental artifacts was observed for lithic specimens, glass, and to a lesser degree, organic specimens. The quartzite flake sustained thermal fractures resulting in two fragments on the distal portion of the flake where the material was thinnest. Peak upper surface and lower surface temperatures associated with this specimen were 561.7°C and 191.9°C respectively. The chert core specimen exhibited two linear surface cracks radiating from the same point of origin, and traversed across the entire upper surface of the specimen. The peak upper surface temperature recorded for this specimen was 541.3°C and the peak lower surface temperature was 102.7°C. The Pecos chert biface exhibited a small (12.4mm) linear surface crack on the upper surface radiating from the distal end of the specimen. Peak upper and lower surface temperatures recorded for this specimen ranged between 440.8-145.1°C. Longer flame lengths observed during trial #4 produced peak upper and lower surface temperatures of 649.7-382.1°C at the rear of the sediment bed where the sandstone block was positioned; however, thermal alteration of the block was limited to an linear band of oxidation along the leading edge of the upper surface of the specimen. No thermal fracturing or spalling was observed. The glass specimen (historic medicine bottle fragment) sustained thermal fractures resulting in three fragments when subjected to peak upper and lower surface temperatures of 414.2-291.0°C. Bone and antler specimens exhibited moderate charring, propagation of surface cracks, and weight reductions of 3-4%. The shell specimen sustained a weight reduction of approximately 8% as well as moderate delamination of its interior surface. All organic specimens were noticeably more friable during handling after the simulation. Peak upper and lower surface temperatures for these specimens generally fell within the 500°C and 100°C ranges.

<u>Trial #5</u>

Trial #5 replicated the experimental conditions defined for Trial #4. Video analysis of flaming combustion during this trial showed maximum flames lengths of 1.2m, heights of 0.66m, and angle of 54.5°. Total heat flux measured at the soil surface was 54.6 kw/m^2, radiant soil flux was 33.1 kw/m^2, total air flux measured at 25cm above the sediment bed was 85.1 kw/m^2 and radiant air flux was 39.2 kw/m^2. Peak temperatures attained from the upper surfaces of artifact ranged between 689.6-286.5°C, with most peaking at 500-600°C. These temperatures reached apex levels within 30-60 seconds and where sustained for 12-37 seconds. Peak lower surface temperatures ranged widely between 220.7-39.9°C, although temperatures generally were recorded in the 100-200°C range. Time/temperature curves were precipitous and serrated for upper surface thermocouples, but more evenly protracted for lower surface thermocouples. Time/temperature and heat flux curves are provided in Appendix 3, Figure 4.1) and Figure 4.15, data CD.

Thermal alteration of experimental artifacts during this trial was similar to that described for the previous trial, in that the exposed surfaces of all specimens were blackened by soot and combustive tar. However, the extent of significant thermal alteration observed during this trial was somewhat less than that observed for trial #4. Significant thermal alteration was limited to the chert core, glass, and organic specimens. The chert core exhibited one potlid fracture on its upper surface as well as two linear surface cracks that radiated from near the potlid scar. The peak upper surface temperature recorded for this specimen was 415.9°C, and peak temperature recorded from its lower surface was 101.5°C. The sandstone block section exhibited a thin linear section of oxidation along the leading edge of the upper surface where maximum temperatures reached 689.6°C. Again, heating of this specimen was enhanced due to the longer flame lengths produced by combustion of the cribbed fuels. The glass specimen (historic amber screw-top) sustained thermal fracturing that produced four fragments as well as one linear crack radiating from the vicinity of the fracture surface. Peak upper and lower surface temperatures for this specimen ranged between 573.6-39.9°C. The bone specimen (weathered deer tibia section) sustained significant enhancement of existing surface cracks in which the cracks became large fissures under thermal stress. The bone and antler specimens exhibited charring on upper surfaces and weight reductions of approximately 3% due to the partial combustion of the organic phase. The shell specimen sustained a weight reduction of 2% as well as moderate delamination of its interior surface. In general, peak upper and lower surface temperatures recorded for organic specimens were recorded in the 600°C and 100°C ranges.

<u>Trial #6</u>

Trial #6 replicated the moderate fuel load and high wind velocity treatment defined for the previous two trials. Combustion of cribbed fuels during this trial produced flame lengths of 1.1m, heights of 0.71m, and flame angle of 49.2°. Peak heat flux measurements recorded at the sediment surface were 42.8 kw/m^2 for total flux and 18.9 kw/m^2 for radiant flux; and those recorded 25cm above the sediment surface were 45.1 kw/m^2 for total flux and 22.5 kw/m^2 for radiant flux. Peak temperature recorded from the upper surfaces of artifacts ranged between 702.0-321.1°C, with the majority registering between 500-600°C. These temperatures generally reached apex levels within 30-60 seconds and were sustained for a period of 12-37 seconds. Peak temperatures measured from the lower surfaces of artifacts ranged widely between 201.4-34.50°C, although most maximum lower surface temperatures were recorded in the 100-200°C range. Time/temperature data show sharp rises to the apexes for upper surface maximum temperatures and more uniformly rounded curves for lower surface thermocouples. Time/temperature and heat flux/time curves for Trial #6 are provided in Appendix 3, Figure 4.16 and Figure 4.17, data CD.

As reported for the previous two trials, each artifact burned during this simulation exhibited combustive residue deposits, soot and tar, on upper surfaces giving the artifact a blackened appearance. Significant thermal alteration was observed for some lithic, glass, and to a lesser extent, organic specimens. The quartzite flake sustained one small fracture scar on the proximal end (fragment not recovered) and a deep linear surface crack (completely through flake body) that extended across the entire specimen. The fracture scar also exhibited mineral oxidation in which the original brown color was altered to reddish brown. Peak upper and lower surface temperatures recorded for this specimen were 476.5-123.3°C. The chert core sustained significant thermal fracturing on the upper surface of the nodule on the side orientated closest to the fuel bed, where thermal stress generated five fragments. Each of the fragments sustained mineral oxidation in which the original color was altered from yellowish brown to dusky red. In addition, one of the fragments exhibited a potlid fracture, and the core body exhibited a linear fracture radiating from the area of significant fracturing and across the upper surface of the specimen. The peak temperature recorded on the upper surface of this specimen was 456.1°C and the peak lower surface temperature was 111.9°C. The sandstone block section exhibited minor oxidation along the leading edge of the upper surface under a maximum upper surface temperature of 702.0°C. Again, this temperature was elevated due to increased flame lengths associated with cribbed fuels. The glass specimen (historic preserve jar) sustained one thermal fracture along the lip of the container, generating one detached fragment as well as one linear crack radiating from the same area. The peak temperatures associated with this specimen were 311.5°C and 37.3°C for the upper and lower surfaces respectively. Organic specimens sustained partial combustion and weight reductions in the 1-3% range. Delamination of the interior surface of shell and crack enhancement of preexisting surface cracks on the bone specimen were also observed. These specimens were subjected to peak upper and lower surface temperatures in the 600°C and 100°C ranges.

Moderate-Light Fuel Load / High Wind Velocity Condition (Trials #7-9)

The third set of wildland fire simulations incorporated a moderate-light fuel load (4.34 ton/acre) (1597.35 kg/ha) and a high wind velocity. The treatment is similar to that used for the previous simulations, but with a reduced fuel load. Shredded excelsior was used as fuel during this simulation. In total, three trials were conducted under this experimental treatment (Trials #7-9).

Trial #7

Flaming combustion during trial #7 generated peak heat flux readings of 35.5 kw/m^2 total soil flux, 14.4 kw/m^2 for radiant soil flux, 43.6 kw/m^2 for air total flux, and 17.4 kw/m^2 for air radiant flux. Flame data for trial #7 is not available due to a malfunction with the video system. Peak temperatures measured by thermocouples placed on the upper surfaces of artifacts ranged between 664.9-337.9°C. Peak upper surface temperatures were reached within approximately 20-50 seconds and sustained for a period of 9-20 seconds. Maximum temperatures measured by thermocouples positioned on the lower surfaces of artifacts varied widely between 208.9-36.5°C, with most falling within the 100-200°C range. Heat flux data and time/temperature curves for upper and lower surface thermocouples are provided in graphical form in Appendix 3, Figure 4.18 and Figure 4.19, data CD.

As observed during previous trials, all experimental artifacts exhibited combustive residue deposits on upper surfaces giving specimens a blackened appearance. Significant thermal alteration of experimental artifacts during trial #7 was limited to the chert core, glass, and to a lesser extent, obsidian and organic materials. The chert core exhibited significant thermal fracturing along the upper surface of the nodule (closest to fuels) in which 24 small fragments were observed. In addition, mineral oxidation was observed on 20 fragments in which color was altered from 10YR5/6 (yellowish brown) pre-burn to10R3/4 (dusky red). Eleven potlid fractures were also observed on seven of the fragments. The peak temperature recorded from the upper surface of this specimen was 552.4°C. This contrasts starkly to the 83.4°C peak temperature recorded from the lower surface of the specimen. The sandstone block exhibited minor oxidation resulting in a thin linear reddened area along the leading edge of the upper surface. The peak temperature recorded on the upper surface of this specimen was 531.7°C. Enhancement of preexisting radial fracture lines was observed on the upper surface of the obsidian specimen (black and gray banded blade) where the peak temperature reached 572.8°C. The glass specimen (historic ink jar) sustained two undulated linear surface cracks that traversed then entire circumference of the vessel. Peak upper and lower surface temperatures recorded for the ink jar were 337.9-123.9°C. Organic specimens exhibited moderate charring, particularly on upper surfaces, as well as partial combustion resulting in reductions in mass of 1-2%. In addition, the weathered bone specimens exhibited enhancement of existing surface cracks, and the shell specimen sustained delamination of it interior surface. Peak upper surface temperatures recorded for organic specimens ranged between 664.9-512.9°C.

Trial #8

Trial #8 replicated the fuel load and wind velocity treatment defined for the previous trial. Flaming combustion of shredded excelsior during this trial generated flame lengths of 0.76m, heights of 0.38m, and angles in the 58.3° range. Heat flux measurements recorded at the sediment surface were 47.3 kw/m^2 for total soil flux, 19.9 kw/m^2 for radiant soil flux, 57.3 kw/m^2 for total air flux, and 19.2 kw/m^2 for radiant air flux. Peak temperatures measured on the upper surfaces of experimental artifacts varied widely between 819.0-397.5°C, with most falling within the 500-700°C range. These temperatures peaked within a period of 30-50 seconds and were sustained at high temperature briefly between 7-26 seconds. Graphical heat flux data and time/temperature curves generated for upper and lower surface thermocouples are provided in Appendix 3, Figure 4.20 and Figure (4.21, data CD). The high maximum upper surface temperatures recorded during this trial may be a function of the steep flame angle of 58.3° observed during combustion. In effect, the steep flame angle, driven by a high wind velocity, brought the flames closer to the upper surface of artifacts and the sediment surface. Although the residence times of peak temperature were shorter due to reduced fuel load, the flame produced high temperatures and significant levels of radiant heat energy at the sediment surface.

Thermal alteration of experimental artifacts was characterized by the deposition of combustive residues on the upper surfaces of all specimens, giving them a blackened appearance. Significant thermal alteration was observed for the chert core, chert biface, glass, and to a lesser degree, obsidian and organic materials. The chert core sustained thermal fractures resulting in one large fragment and two small fragments on the portion of the specimen positioned closest to the fuel bed. In addition, the two small fragments exhibited mineral oxidation that altered their color from yellowish brown to dusky red. The peak upper and lower surface temperatures recorded for this specimen were 470.5°C and 195.1°C respectively. The chert biface was subjected to a maximum upper surface temperature of 819.0°C, and a maximum lower surface temperature of 238.5°C. As a result, the biface sustained a linear fracture through its midsection resulting in the fragmentation of the biface into two halves. The fracture somewhat resembled a snap fracture; however, this thermally induced stress fracture was slightly more undulating in appearance. Thermal alteration of the obsidian specimen (black and gray banded blade) was characterized by the propagation of existing radial fracture lines on the upper surface where the maximum temperature peaked at 754.0°C. The sandstone block section exhibited minor oxidative reddening along the leading edge of the upper surface where temperatures reached 432.3°C. The glass specimen (historic medicine bottle) sustained thermal fracturing on the proximal end, which produced three fragments. Peak upper and lower surface temperatures for this specimen varied widely between 727.0°C and 65.6°C. Peak upper surface temperatures associated with organic specimens ranged between 705.0-504.1°C. As a result, organic specimens exhibited slight charring of upper surfaces and partial combustion resulting in weight losses of 1.6-2.6%, as well as shell delamination and enhancement of existing surface cracks. These specimens also became noticeably more friable during handling after the fire simulation.

Trial #9

Trial #9 was the final replicate trial conducted under the moderate-light / high wind velocity experimental treatment. Flaming combustion during this simulation produced maximum flame lengths of 0.76m, heights of 0.46m, and angle of 52.0°. Heat energy produced by flaming combustion generated peak heat flux measurements of 38.0 kw/m^2 for soil total flux, 22.0 kw/m^2 for soil radiant flux, 49.1 kw/m^2 for air total flux, and 23.0 kw/m^2 for air radiant flux. Peak temperatures recorded on the upper surfaces of artifacts ranged between 592.3-287.2°C, with most registering in the 400-500°C range. Temperatures ascended to apex levels within approximately 10-40 seconds, and temperatures at the upper end of the spectrum were sustained for 8-32 seconds. Maximum temperatures measured at the interface between the sediment surface and the under side of artifacts varied widely between 343.0-80.9°C, with most temperatures falling within 100-200°C. The flame angle recorded for this trial (52.9°) was not as extreme as that recorded for trial #8 (58.3°), thus peak upper surface temperatures and soil total flux readings were diminished during thus trial as compared to trial #8. The time/temperature curves generated from upper and lower surface thermocouples, and accompanying graphical heat flux data are provided in Appendix 3, Figure 4.22 and 4.23, data CD.

Thermal alteration of experimental artifacts included moderate combustive residue deposits on the exposed surfaces of all artifacts giving them a blackened appearance. Significant thermal alteration was observed for the quartzite flake, chert core, and to a lesser degree, obsidian and organic specimens. The quartzite flake sustained a thermal fracture near the distal end of the flake where the material was thinnest. The thermal fracture produced one fragment, and mineral oxidation was observed along the fracture surface in which the color altered from brown to reddish brown. Peak upper and lower surface temperatures associated with this specimen were 435.5-160.9°C respectively. Thermal alteration of the chert core included a fracture at approximately midpoint resulting in one large fragment. The fragment also exhibited a thermal spall scar and minor mineral oxidation in which the color was altered from yellowish brown to dusky red. Peak upper and lower surface temperature associated with thermal alteration of the chert core ranged between 513.8-165.9°C. The obsidian blade exhibited the propagation of existing radial fracture lines on the upper surface of the specimen where the peak temperature reached 592.3°C. Thermal alteration of organic specimens included light to moderate charring on upper surfaces, partial combustion resulting in weight losses of 1-4%, enhancement of existing surface cracks, and delamination of the interior shell surface. These specimens were also more friable post-heating where peak temperatures reached 566.2-525.4°C.

Light Fuel Load / High Wind Velocity Condition (Trial #26)

One simulation was conducted using an experimental treatment of light fuel load, 1.00 ton/acre (368.05 kg/ha), paired with high wind velocity. These conditions are roughly analogous to moderate intensity wildland fires and prescribed fires in grassland fuels. This treatment was performed only once since the results of the first trial were very predictable.

Flaming combustion of lightly loaded excelsior produced maximum flame heights of 0.37m, lengths of 0.52m, and angle of 44.4°. Peak temperatures measured on the upper surfaces of experimental artifacts ranged between 498.9-220.2°C. The 498.9°C reading is an outlier with most maximum upper surface temperatures ranging between 200-400°C. Peak upper surface temperatures ascended to their apexes within 20-25 seconds, but high temperatures were sustained briefly for only 4-10 seconds. Maximum lower surface temperatures varied widely between 287.2-52.2°C, although most temperatures peaked within the 50-100°C range. Peak heat flux measurements were also low to moderate (24.5 kw/m^2 soil total flux, 12.5 kw/m^2 soil radiant flux, 27.9 kw/m^2 air total flux, 14.1 kw/m^2 air radiant flux) indicating minimal fire severity. Time and temperature curves for upper surface thermocouples ascended and descended sharply while those generated for the lower surface thermocouples were more protracted. Time/temperature curves and graphical heat flux data for trial #26 are provided in Appendix 3, Figure 4.24 and Figure 4.25, data CD.

Thermal alteration of experimental artifacts during this trial was minimal. The only macroscopically discernable affect of the simulation on the artifacts was the deposition of a light combustive residue. Organic specimens exhibited very light charring on upper surface edges as well as reductions in pre-burn mass of far less than 1%. No significant forms of thermal alteration such as fracturing or cracking were observed for any of the experimental artifacts. The minimal extent of thermal alteration to experimental artifacts is a function of low to moderate peak upper surface temperatures, brief residence times, and minimal release of heat energy generated by the combustion of light fuels. The fuel load was not sufficient to produce sustained high temperatures and heat flux at the surface of the sediment bed. These results are consistent with those recorded under field conditions during prescribed burns in grassland fuels at Badlands National Park (Buenger 2002). Replicates of this trial were deemed unnecessary due to the low heat yields and limited potential for observable thermal alteration of experimental artifacts under the low fuel load treatment.

Heavy Fuel Load / Low Wind Velocity Condition (Trials #13-15)

Following the wildland fire simulations in which each representative fuel load was paired with a high wind velocity experimental condition, wildland fire simulations were performed using a low wind velocity treatment of 2-3 mph (3.2-4.8 kph) for each of the previously defined fuel loadings. These simulations were performed to approximate field conditions where wind velocity and fire severity are of reduced intensity over that simulated with the high wind velocity treatments. The first rounds of fire simulations conducted using the low wind velocity condition were those paired with the previously defined heavy fuel load treatment. Three simulations under the heavy fuel load / low wind velocity treatment were performed (trials #13-15). In addition, three added fire simulations were conducted where fuels were placed on the sediment bed and experimental artifacts (trials #19-21). These simulations were performed to simulate field conditions where a heavy duff accumulation is present above the mineral soil surface. These simulations are defined under the fuel on artifacts, heavy fuel load / low wind velocity experimental condition.

Trial #13

The first trial produced flaming combustion of heavily loaded excelsior fuels where flames reached a maximum length of 1.2m, height of 0.85m, and angle of 43.5°. Compared to the previous heavy fuel load / high wind velocity simulations, flame lengths and heights were enhanced when wind velocity was reduced. However, the flame angle under the low wind velocity was reduced by as much as 12° compared to the heavy fuel load / high wind velocity wildland fire simulations. Peak heat flux measurements ranged from 48.2 kw/m^2 for total soil flux, 32.0 kw/m^2 for soil radiant flux, 81.5 kw/m^2 for total air flux, and 36.9 kw/m^2

for radiant air flux. The 81.5 kw/m^2 maximum value for total air flux is considerably higher than that previously recorded during other simulations; and is likely a function of more heat energy being radiated upwards into the air under reduced flame angle. Maximum temperatures measured by thermocouples placed on the upper surfaces of artifacts varied between 608.8-398.0°C, with most falling within the 400-500°C range. Peak upper surface temperatures were attained within 50-60 seconds with high temperatures being sustained for 20-40 seconds. These maximum temperatures and residence times are of diminished capacity compared to that recorded during the high fuel load / high wind velocity trials. Again, reduced flame angle is probably the key variable associated with this observation. Maximum temperatures measured by thermocouples placed at the interface between the sediment bed and lower artifact surfaces during trial #13 ranged widely between 310.1-47.33°C, with most falling with the 100-200°C range. These temperatures are also lower than those recorded during simulations using the same fuel load, but under high wind velocity. Graphical time/temperature and heat flux data are provided in Appendix 3, Figure 26 and Figure 27, data CD.

Thermal alteration of experimental artifacts burned during trial #13 was characterized by the deposition moderate to heavy combustive residue, primarily on the upper surfaces of artifacts. Significant thermal alteration of artifacts was limited to the quartzite flake, chert core, and to a lesser degree obsidian and organic materials. The quartzite flake did not exhibit evidence of thermal fracturing; however, a color alteration from brown to reddish brown induced by mineral oxidation was observed at the distal end of the flake where the material is thinnest. The maximum upper surface temperature recorded for this specimen was 464.2°C. The chert core did sustain one large thermal fracture in which the entire specimen was essentially bisected. In addition, one small potlid fracture was also observed on the upper surface of the specimen. Peak upper and lower surface temperatures recorded for this specimen were 563.2°C and 153.4°C respectively. Enhancement of existing radial fracture lines on the upper surface of the obsidian specimen was observed where the peak temperature reached 608.8°C and the maximum lower surface temperature was 310.0°C. The shell specimen (small, unspecified species) sustained three linear cracks originating from the beak area. Peak upper and lower surface temperatures for this specimen ranged between 440.4-71.8°C respectively. Enhancement of existing surface cracks on the bone specimen were observed as well in association with a peak upper surface temperature of 450.2°C. Partial combustion of organic material resulted in weight reductions of 3.3-4.6% for antler, bone, and shell. The range of significant thermal alteration observed for experimental artifacts during this trial is less severe than that observed for artifacts burned under previous simulations using the same fuel load and high wind velocity. This is a function of reduced flame angle and subsequent lower surface temperatures and levels of radiant heat energy being released downwards to the sediment bed.

Trial #14

Trial #14 was a replicate simulation using the treatment defined above. Flaming combustion of heavily loaded excelsior fuels during this simulation generated flame dimensions similar to that recorded for the previous trial. Video analysis of the simulation shows that a reduced wind velocity is generated sizeable flame length of 1.2m, heights of 0.84m and a reduced angle of 44.5°. Maximum heat flux measurements ranged from 50.0 kw/m^2 for total soil flux, 31.7 kw/m^2 for radiant soil flux, 76.5 kw/m^2 for total air flux, and 37.1 kw/m^2 for radiant air flux. As recorded for the previous trial, the high total air flux value may be attributed to a reduced flame angle, which promoted an increase in heat energy release towards the atmosphere. Maximum temperatures recorded by thermocouples positioned on the upper surfaces of experimental artifacts ranged between 582.5-328.2°C, with most falling within 400-500°C. These maximum temperatures were reached within 25-50 seconds and remained elevated at high levels briefly for 10-29 seconds. Peak temperatures recorded at the lower surfaces of artifacts varied widely between 230.7-41.3°C, with most falling within the 100-200°C range. Time/temperature and heat flux data are summarized graphically in Appendix 3, Figure 4.28, and Figure 4.29, data CD. Overall, the flame, temperature, and heat flux data recorded during trial #14 are similar to those presented for Trial #13.

Thermal alteration of experimental artifacts was also consistent for this trial and the previous one, although the prevalence of significant forms of thermal alteration was somewhat reduced. The most pervasive form of thermal alteration observed was moderate to heavy combustive residue deposits adhering to the upper surfaces of artifacts producing a blackened appearance. Significant forms of thermal alteration were observed for the glass specimen, and to a lesser extent, obsidian and organic materials. Thermal fracturing of chert and quartzite lithic specimens was not observed. The glass specimen (modern beverage container fragment) sustained one thermal fracture resulting in a single fragment. Peak upper and lower surface temperatures associated with this specimen were 450.6°C and 41.25°C respectively. The obsidian specimen (black and gray banded blade) exhibited the propagation of existing radial fracture lines on the upper surface where peak temperatures reached 582.5°C. Organic specimens sustained weight reductions of 1.5-3.0% as well as thermal fracturing of shell and the enhancement of surface cracks on the upper surface of the bone specimen. Peak upper surface temperatures recorded for organic specimens ranged between 376.8-422.2°C. Overall, the limited thermal alteration of experimental artifacts may be attributed to reduced peak surface temperatures and radiant heat flux at the soil surface resulting from reduced flame angle. The results presented for trial #14 are consistent with those summarized for the previous trial.

Trial #15

Trial #15 was the final replicate performed under the heavy fuel load / low wind velocity treatment. Flaming combustion of excelsior fuels produced flames measuring 0.76m in height, 1.1m in length, and a flame angle of 46.6°. Peak heat flux measurements varied between 52.2 kw/m^2 for total soil flux, 24.2 kw/m^2 for soil radiant flux, 82.8 kw/m^2 for total air flux, and 29.1 kw/m^2 for radiant air flux. As observed during the previous two simulations, the high total air flux value is a function of reduced flame angle and the release of more heat energy upwards toward the atmosphere and away from the sediment surface. Peak temperatures recorded on the upper surfaces of artifacts ranged between 509.2-394.2°C, whereas peak lower surface temperatures varied widely between 229.5-43.5°C with most falling within the 100-200°C range. Maximum upper surface temperatures peaked sharply within 40-50 seconds and were sustained for approximately 14-28 seconds. Conversely, lower surface temperature ascents, apexes, and decants were more protracted. Graphical time/temperature and heat flux data are provided in Appendix 3, Figure 4.30, Figure 4.31, data CD. Flame, temperature, and heat flux data generated during this simulation are consistent with those recorded for the previous two simulations using the same fuel load and wind velocity experimental condition.

The range of thermal alteration of experimental artifacts observed during trial #15 was also similar, albeit somewhat reduced over that recorded for the prior two trials. The most pervasive form of thermal alteration observed was the deposition of moderate to heavy combustive residues on the upper surfaces of artifacts. More significant forms of thermal alteration were observed for obsidian and organic specimens only. The obsidian blade exhibited the propagation of radial fracture lines on the specimen's upper surface where the maximum temperature reached 509.2°C. The shell specimen sustained two linear fractures radiating from the beak and the enhancement of existing linear surface cracks was observed for the bone specimen. Partial combustion of organic specimens resulted in weight reductions ranging between 2-4%. Peak upper surface temperatures associated with organic specimens fell within the 506.2-394.2°C range.

Heavy Fuel Load / Low Wind Velocity Condition (Fuel on Artifacts) (Trials #19-21)

Three additional wildland fire simulations were performed using the heavy fuel load / low wind velocity treatment, but also including the additional variable of added fuel placed on the sediment bed and experimental artifacts. These trials, #19-21, were conducted to simulate heavy fuel load environments in which significant duff accumulation is present above the mineral soil surface where archaeological materials may be present.

Trial #19

Flaming combustion of heavily loaded excelsior fuels generated large flames measuring 0.90m in height and 1.3m in length. Low wind velocity reduced flame tilt to 46.5°, compared to the 50° + flame angles measured under trial conducted using the same fuel load and a high wind velocity. The low wind velocity and resultant reduced flame angle also promoted enhanced total air flux and radiant air flux values of 89.9 kw/m^2, and 36.6 kw/m^2 respectively, which indicates that much of the potential heat energy generated during combustion was released upwards into the atmosphere of the wind tunnel. The peak total soil flux value was measured at 23.6 kw/m^2; however, the radiant soil flux value of 2.7 kw/m^2 is significantly diminished over the 24-32 kw/m^2 peak value recorded for simulations using the same experimental treatment minus fuel placement on the sediment bed (trial #13-15). This suggests that combusting fuels located directly above the sediment surface reduce the potential for significant radiation of heat energy below the fuels. This contrasts with previous trials where the full potential of heat energy was radiated towards the sediment surface due to direct contact from flames being pushed over the sediment bed from upwind fuels. However, although radiant heat energy output at the sediment surface was significantly diminished during the trial, peak temperatures measured by thermocouples positioned on the upper surfaces of artifacts were consistent with those recorded during trials #13-15, generally falling within the 400-500°C range. Peak upper surface temperature recorded during trial #19 ranged between 630.5-460.4°C, with most maximums falling within the 400-500°C range. The major difference in upper surface artifact heating between the fuel on artifact and no fuel on artifact trials is the rate at which temperatures reached apex levels. During trial #19, peak upper surface temperatures were achieved over a protracted period of 70-135 seconds due to fuel placement on artifacts, which contrasts sharply with the 30-60 second intervals recorded during trials where fuels were absent on artifact surfaces. Peak lower artifact surface temperatures for trial #19 ranged widely between 446.2-68.1°C; however, most maximums fell within the 100-200°C range. These temperature are also consistent with those recorded during trials #13-15, but the point of contrast again is heating rate, which was considerably more protracted during trial #19. Time / temperature data, and heat flux data for trial #19 are provided in graphical form in Appendix 3, Figure 4.32 and Figure 4.33, data CD.

The major difference between the fuel present on artifacts and fuel absent on artifacts simulations is the rate of heating. When artifacts come into direct contact with tilted flames pushed over their upper surfaces, the rate of heating is more severe as compared to artifacts positioned directly under fuels that experience more prolonged and even rates of heating. Thus the potential for significant thermal alteration of artifacts is likely to be greater under severe rates of heating due to a greater potential for differential thermal stress.

Thermal alteration of experimental artifacts during trial #19 was characterized by extensive, deep black combustive residue deposition. This deposit was considerably darker and more pervasive than combustive residue deposits observed during trials #13-15. In effect, the fuel above the artifacts created a reducing atmosphere in which specimens became deeply blackened during fuel combustion. However, the extent of thermal significant thermal alteration observed for trial #19 was not as extensive as that observed for the fuel absent trials. This supports the data discussed above regarding rate of artifact heating during fuel present and fuel absent simulations. Significant thermal alteration was limited to shell and bone specimens only. These specimens exhibited surface cracking as well as partial combustion resulting in weight reduction of 2-3%. Thermal fracturing of lithics, glass, or the enhancement of radial fracture lines on obsidian artifacts was not observed. This contrasts with the extent of significant thermal alteration observed during trials #13-15 (see above sections). In effect, fuel placement on artifact prolonged the rate of heating and reduced the potential for significant thermal alteration generated by thermal shock.

Trial #20

Trial #20 was performed as a replicate simulation under the fuel on artifact, heavy fuel load / low wind velocity experimental treatment. The results of this trial were largely consistent with those recorded for trial #19. Combustion of excelsior fuels generated large flames measuring 0.9m in height and 1.4m in length. Low wind velocity limited flame angle to 45.0°, and also produced elevated peak total air flux and radiant air flux values of 76.1 kw/m^2 and 26.2 kw/m^2. As observed during previous low wind velocity trials, much of the potential heat energy generated during combustion was released upwards, away from the sediment surface. This, combined with the reducing effect of fuel placement on the sediment bed, generated a low peak radiant soil flux value of 10.6 kw/m^2. This value is greater than the reading recorded for the previous trial, but remains significantly lower that the levels recorded during the fuel absent simulations. Peak temperatures measured on the upper surfaces of artifacts were consistent with those reported for the previous trial, generally falling within the 400-500°C range with outlier values of 603.8°C and 463.9°C. These temperatures peaked over a prolonged period of 75-140 seconds and were sustained at high levels for 11-48 seconds. Lower surface temperatures ranged widely between 446.2-64.6°C due to variable artifact size and potential gaps present between the artifact and sediment surface, although most maximum values fell within the 100-200°C range. Peak lower surface temperature rose more gradually over a longer period compared to upper surface maximum temperatures. Graphical representation of time / temperature and heat flux data for trial #20 are presented in Appendix 3, Figure 4.34 and Figure 4.35, data CD.

Thermal alteration of trial #20 experimental artifacts was generally consistent with that described for the previous trial where most artifacts were deeply blackened by combustive residue produced in a reducing environment. The only exception to this trend is that the chert core sustained one small thermal spall on its upper surface and mineral color alteration of the fracture scar under a peak upper surface temperature of 575.4°C. Thermal alteration of bone and shell was consistent with that observed during the previous trial, and partial combustion of organic specimens resulted in weight reductions of 4-6%. Overall, the results of the replicate trial were consistent with the first simulation performed under the fuel on artifact, heavy fuel load / low wind velocity experimental condition.

Trial #21

Trial #21 was the final replicate simulation performed under the present experimental treatment. The results of this simulation were quite consistent with those reported for the previous two trials. During the simulation, combusting fuel generated flame lengths of 1.2m and heights of 0.9m. Low wind velocity limited flame angle to 43.4°, which also contributed to an elevated total air flux value of 85.2 kw/m^2. Dispersed energy into the wind tunnel atmosphere combined with the reducing effect produced by fuel placement on the sediment bed significantly limited soil radiant flux to only 3.1 kw/m^2. Peak upper and lower surface temperatures generally fell within the 400-500°C and 100-200 °C ranges respectively. Artifact heating rates were protracted under the reducing environment, ranging between 80-200 seconds for upper surface peaks. Time / temperature and heat flux data are summarized graphically in Appendix 3, Figure 4.36 and Figure 4.37, data CD.

Thermal alteration was also consistent with that observed during the previous two trials. All artifacts were heavily blackened on exposed surfaces due to heavy combustive residue deposits produced in a reducing environment. The chert core exhibited one small thermal spall on its upper surface as well as mineral oxidation within the fracture scar. The peak upper surface temperature recorded for this specimen was 402.0°C. Shell and bone specimens exhibited thermal cracking, and all organic specimens sustained weigh reductions of 1-6% resulting from partial combustion.

Moderate Fuel Load / Low Wind Velocity Condition (Trials #16-18)

Continuing with the low wind velocity treatment, the fuel load was reduced to 6.33 ton/acre (2329.77 kg/ha) for trials #16-18 to create the moderate fuel load / low wind velocity experimental condition. Fuel loading was accomplished as previously defined moderate fuel load treatment using cribbed fuels.

<u>Trial #16</u>

Flaming combustion of cribbed fuels during trial #16 produced a maximum flame length of 1.1m, height of 0.82m, and angle of 38.8°. Peak heat flux measurements recorded during the simulation were 45.7 kw/m^2 for total soil flux, 26.6 kw/m^2 for radiant soil flux, 80.2 kw/m^2 for total air flux, and 21.0 kw/m^2 for radiant air flux. As previously noted during the heavy fuel load / low wind velocity trials, a wind velocity of 2-3 mph results in a lower flame angles, less than 40° in this instance. The high peak air flux value is a product of low flame angle and the subsequent increase in the amount of heat energy released upwards during flaming combustion. Peak temperatures measured by thermocouples placed on the upper surfaces of artifacts also reflect this trend. Most maximum upper surface temperatures fell within the 300-400°C range with outlier values of 524.6°C and 394.5°C. Trials conducted using the same fuel load, but high wind velocity generated peak upper surface temperatures in the 500-600°C range. Maximum lower surface temperatures during trial #16 ranged between 220.8-83.8° with most peak values falling within 100-200°C. These temperatures are consistent with lower surface temperatures record during previous trials. In general, the rate of heating on the upper surfaces of artifacts was precipitous as compared to the rated of heating experienced at the interface between the sediment bed and the lower surfaces of artifacts. Graphical time/temperature and heat flux data are provided in Appendix 3, Figure 4.38 and Figure 4.39, data CD.

Thermal alteration of all experimental artifacts burned during the simulation consisted of light to moderate combustive residue deposits on exposed artifact surfaces. Significant thermal alteration of artifacts was limited to the Hartville Uplift chert nodule and organic materials. The chert core exhibited one thermal spall on the upper surface as well as a linear surface crack running approximately one-half the circumference of the specimen. Peak upper and lower surface temperatures associated with this specimen were 349.3°C and 92.0°C resulting in a temperature differential of approximately 74%. The shell specimen (small species) sustained two linear cracks under thermal stress incurred by peak upper and lower surface temperatures of 437.7-220.8°C (47.9% differential). Bone and antler specimens sustained minor charring of upper surfaces under similar conditions. Partial combustion of organic materials resulted in weight losses of 1.6-2.5%. Overall, the extent of thermal alteration observed during the first moderate fuel load / low wind velocity simulation was diminished in comparison to that observed during trial under the same fuel load and high wind velocity. In sum, this is largely attributed to the lower peak upper surface temperatures recorded from artifacts and the increase in potential heat energy release into the atmosphere created under the low wind velocity treatment.

Trial #17

Trial #17 was a replicate simulation under the moderate fuel load / low wind velocity treatment. The results of this simulation are consistent with those reported for the previous trial. Flaming combustion of cribbed fuels during the simulation produced a maximum flame length of 1.1m, height of 0.82m, and angle of 41.6°. Peak heat flux measurements recorded during fuel combustion were 36.7 kw/m^2 for total soil flux, 21.3 kw/m^2 for radiant soil flux, 73.3 kw/m^2 for total air flux, and 16.4 kw/m^2 for radiant air flux. Again, the high total air flux value is a function of reduced flame angle. The other flux values are consistent with previous trials, but the important point is that potential heat energy generated by larger flames was lost to the atmosphere and not emitted towards the sediment bed and artifact surfaces. Artifact peak upper surface temperatures reflect this trend showing consistency with the previous trial and a reduction compared to the high wind velocity trials performed under the same fuel load. Most peak upper surface temperatures fell within the 300-400°C range with outlier values of 568.8°C and 296.7°C. These temperatures reached apex levels within approximately 30-40 seconds and were sustained at high levels for between 9-30 seconds. Maximum lower surface temperatures varied widely from 309.6-78.0°C, although most values fell within the 100-200°C range. As seen during most simulations, upper surface temperatures tend to rise and descend sharply, whereas heating on the lower side of artifact is more gradual and protracted. Time/temperature and heat flux data for trial #17 are provided in graphic form in Appendix 3, Figure 4.40 and Figure 4.41, data CD.

Thermal alteration of experimental artifacts during the trial was consistent with that observed for the previous trial where light to moderate combustive residue deposits on exposed artifact surfaces was pervasive across the entire sample. These deposits ranged from light soot to deeply charred condensate tar, which gave affected artifacts a blackened appearance. Significant thermal alteration of artifacts was also consistent with the previous trial where it was limited to the chert core and organic materials. Notable thermal alteration of the chert core during trial #17 consisted of linear surface cracking along the upper surface. Peak upper and lower surface temperatures associated with this specimen were 353.1-78.0°C (78% differential). The shell specimen (small) also exhibited linear cracking under thermal stress induced by peak upper and lower surface temperatures of 411.6-109.6°C (25% differential). Bone and antler specimens exhibited partial charring along edges and upper surface areas, but not thermal fracturing or crack enhancement was observed. Partial charring and combustion attributed to post-burn mass reductions of 2.5-6.5% for organic specimens. Overall, these results are similar to those recorded for the previous trial, and further suggest that wind velocity and flame angle are important variables that condition potential heat energy output and significant thermal alteration of common artifact material types.

Trial #18

Trial #18 was the third and final wildland fire simulation conducted using the moderate fuel load / low wind velocity experimental condition. Flame data derived from videotape analysis of the simulation show that combusting fuels generated flames lengths of 1.2m, heights of 0.87m, and angles of 41.0°. Peak heat flux data show measurements of 51.9

kw/m^2 for total soil flux, 26.2 kw/m^2 for radiant soil flux, 73.0 kw/m^2 for total air flux, and 14.2 kw/m^2 for radiant air flux. These data are consistent with those recorded for the previous two trials performed under the same fuel and wind treatment. Again, the high total air flux value is a function of large flames and reduced flame angle. Peak upper surface temperatures measured by thermocouples placed on the upper surfaces of artifacts were, however, slightly elevated during trial #18. Maximum temperatures range between 708.0-354.6°C with the majority of values falling within the 400-500°C range. These temperatures peaked within approximately 25-40 seconds and remained at high levels for 4-25 seconds. These elevated maximums may be due to any number of variables, but are most likely attributed to larger flame size and increased potential heat energy output. The 708.0°C value is clearly an outlier, and may be the result of direct flame contact with the thermocouple, or simply a pocket of intense heat energy release near this particular specimen. Maximum lower surface temperatures varied widely as well (309.6-78.0°C), but were consistent with those recorded during previous trials in which most values fell within the 100-200°C range. Graphic representations of time/temperature and heat flux data are provided in Appendix 3, Figure 4.42 and Figure 4.43, data CD.

Thermal alteration of experimental artifacts during trial #18 was essentially parallel to that observed for the previous two trials. Light to moderate combustive residue coated the exposed surfaces of all artifacts, and significant thermal alteration was limited to the chert core and organic materials. The chert core sustained one thermal fracture down the midline that resulted in the specimen being split into halves. This may be due to impurities within the material (impurity observed on the fracture face of both halves), or simply, due to the fact that the maximum upper and lower surface temperatures associated with this specimen ranged between 708.0-354.6°C (56% differential). Nonetheless, this specimen was subjected to significant levels of thermal stress, which induced substantive thermal fracturing. The shell specimen (small) sustained two linear cracks under peak temperatures of 548.0-398.6°C. Bone and antler specimens exhibited partial charring along upper edge surfaces, but no evidence of crack propagation or fracturing. Partial combustion of organics resulted in post-heating mass reductions of 3-8% for shell, bone, and antler. Overall, these results are consistent with the thermal alteration observed during the previous two trials, and further support the assertions made regarding the important relationships between fuels, wind velocity, potential heat energy production, and thermal alteration of experimental artifacts.

Moderate-Light Fuel Load / Low Wind Velocity Condition (Trials #10-12)

The low wind velocity treatment was paired with the moderate-light fuel loading to continue the alternating series of wildland fire simulations in which fuel load and wind velocity are manipulated. In total, three trials were conducted under the moderate-light fuel load (4.33 ton/acre) (1597.35 kg/ha) and low wind velocity experimental treatment. In addition, three simulations (trials #22-24) were run using the same fuel load / wind velocity treatment, but with fuel placed on top of the experimental artifacts to simulate field conditions where a light duff layer is present.

<u>Trial #10</u>

Trial #10 was the first of six trials conducted under the 4.34 ton/acre / low wind velocity treatment. Flaming combustion of shredded excelsior fuels produced a maximum flame length of 1.2m, height of 0.85m, and angle of 43.5°. These relatively large flames generated heat flux measurements of 44.2 kw/m^2 for total soil flux, 28.9 kw/m^2 for soil radiant flux, 86.4 kw/m^2 for total air flux, and 35.4 kw/m^2 for radiant air flux. As observed for the previous trial conducted under low wind velocity condition, the total air flux value for this trial was elevated indicating that a significant amount of heat energy was directed upwards due to reduced flame angle. Peak temperatures measured on the upper surfaces of artifacts varied considerably from 598.5-232.0°C, although the majority of peak temperatures fell within 400-500°C. These temperatures reached apex levels within approximately 30 seconds and were sustained at high temperature for a relatively brief period of 2-20 seconds. Maximum temperatures measured at the lower surface of artifacts also varied broadly with outliers of 340.8°C and 37.7°C, with most maximums falling within the 50-100°C range. Time/temperature and heat flux data from trial #10 are represented graphically in Appendix 3, Figure 4.44 and Figure 4.45, data CD.

Thermal alteration of experimental artifacts burned during the simulation was characterized by combustive residue deposition and limited significant thermal damage. The combustive tar deposits ranged from glossy black to a tacky yellow-brown adhesive. The glossy black deposit represents tar that is at an advanced stage of combustion, whereas the yellow-brown adhesive is simply the tar deposit that has condensed on artifact surfaces, but has not been completely combusted. These deposits are highly nitrogenous condensate tars that form as organic fuels combust over a cooler surface, in this instance exposed artifact surfaces (Yokelson et al. 1997). The deposit can be removed with vigorous scrubbing using a pumice-based soap and water, and therefore, are not considered a significant form of thermal alteration. Significant thermal alteration was limited to the glass specimen, and to a lesser extent, obsidian and organics. The glass specimen sustained minor thermal fracturing under peak upper and low surfaces of 404.5°C and 44.26°C. Thermal alteration of the obsidian blade consisted of radial fracture line propagation. The shell specimen sustained two linear fractures, and the bone specimen exhibited the enhancement of existing surface cracks. All organic specimens, bone, antler, and shell were partially consumed by flaming combustion resulting in mass reductions of less than 1% to nearly 6%. Peak upper surface temperatures associated with organic specimens fell within the mid to upper 400°C range. Reduced fuel load compounded by a lower wind velocity during this trial produced moderate peak temperatures with limited residence times, which subsequently produced insufficient thermal stress to induce pervasive thermal damage across the sample of experimental artifacts.

Trial #11

Trial #11 was a replicate simulation run using the protocols defined above. Flaming combustion produced during trial #11 generated heat flux levels of 57.4 kw/m^2 for total soil flux, 30.7 kw/m^2 for radiant soil flux, 81.2 kw/m^2 for total air flux, and 40.0 kw/m^2 for radiant air flux. Flames generated during the simulation reached maximum lengths of 1.2m, heights of 0.85m, and burned at an angle of 44.5°. The total air flux value is elevated due to reduced flame angle and subsequent increased heat energy release upwards into the atmosphere. Large flames also produced elevated radiant heat flux levels at the sediment surface; however, they did not produce elevated maximum temperatures at the upper surface of artifacts. Peak upper surface temperatures fell within the 400-500°C range with outlier values of 571.5°C and 284.8°C. These temperatures are consistent with those recorded for trial #10. Peak lower surface temperatures were also consistent with the previous trial, falling primarily within the 50-100°C range with outlier values of 243.9-43.0°C. Time and temperature curves associated with upper and lower artifact surfaces as well as heat flux data are provided in graphical form in Appendix 3, Figure 4.46 and Figure 4.47, data CD.

Thermal alteration of experimental artifacts burned during trial #11 was consistent with that observed during the previous trial. Glossy black and yellow-brown tar deposits adhered to exposed surfaces on the entire artifact sample, although the extent of coverage and density varied. As with the previous trial, significant thermal alteration was limited to glass, obsidian, and organic materials. The glass specimen exhibited minor thermal fracturing under highly differential peak upper and lower surface temperatures of 419.2°C and 43.0°C. Thermal alteration of the obsidian blade was limited to the enhancement of existing radial fracture lines on the upper surface where temperatures reached 482.0°C. The shell specimen exhibited two linear fractures, and the bone specimen exhibited surface crack propagation, both under peak upper surface temperatures of 430.0°C and 507.4°C respectively. All organic specimens sustained partial charring/combustion resulting in mass reductions of 1-2.3%. These results are very consistent with those recorded for the previous trial, and further support the assertions made thus far.

Trial #12

Trial #12 consisted of a replicate simulation under the moderate-light / low wind velocity experimental condition. Combustion of shredded excelsior fuels during this simulation produce results fairly consistent with the previous two trials. Maximum flame dimensions generated during fuel combustion measured 1.1m in length, 0.76m in height, and burned at angles of 46.6°. Peak heat flux measurements were 57.7 kw/m^2 for total soil flux, 34.5 kw/m^2 for radiant soil flux, 77.5 kw/m^2 for total air flux, and 44.5 kw/m^2 for total air flux. The total air flux value is slightly lower than that recorded for the previous two trials due to a slightly steeper flame angle. Subsequently, the other heat flux reading are also slightly elevated over previous values due to a increased concentration of heat energy release at the sediment surface. Some peak upper artifact surface temperatures were also elevated as a result, the highest reaching 676.8°C. However, the majority of peak upper surface temperatures fell within the 400-500°C range as recorded for trials #10 and #11. Due to the moderate-light fuel load residence times were rather brief ranging between 2-19 seconds. Peak lower surface temperatures remained consistent, generally falling within the 50-100°C range with outlier values of 314.6°C and 32.4°C. Graphical representations of time/temperature and heat flux data are provided in Appendix 3, Figure 4.48 and Figure 4.49, data CD.

However, slightly elevated soil flux measurements and limited peak upper surface temperatures on the high end of the spectrum did not affect the range of thermal alteration of artifacts observed during trial #12. Thermal alteration was consistent with that observed during the previous two trials. Tacky yellow-brown and smooth glossy black combustive tar deposits coated exposed surfaces of artifacts, and significant thermal alteration was limited to obsidian and organics. The obsidian blade sustained radial fracture line propagation under thermal stress induced by peak upper and lower surface temperatures of 576.9-144.6°C. One linear thermal fracture was observed on the shell specimen, which experienced limited peak upper and lower surface temperatures of 269.2-100.5°C. Minor enhancement of existing surface cracks on the upper surface of the bone specimen were also observed under peak upper and lower surface temperatures of 461.0-314.4°C. All organic specimens were partially combusted and lightly charred on upper edge surfaces resulting in weight losses of 1-2%. In sum, these results are consistent with those observed during the previous simulations conducted using the moderate-light / low wind velocity experimental treatment.

Moderate-Light Fuel Load / Low Wind Velocity Condition (Fuel on Artifacts) (Trials #22-24)

<u>Trial #22</u>

Trial #22 was the first of three trials performed with fuels placed on top of artifacts and the sediment bed in continuation with the moderate-light fuel load / low wind velocity experimental treatment. Flaming combustion of shredded excelsior fuel during the simulation generated a maximum flame length of 1.3m, height of 0.86m, and angle of 46.5°. These flames were of enhanced size compared to those recorded during trials #10-12 where fuels were not placed on the sediment bed and artifacts. Peak heat flux measurements recorded during trial #22 were 71.3 kw/m^2 for total soil flux, 8.3 kw/m^2 for soil radiant flux, 92.0 kw/m^2 for total air flux, and 41.8 kw/m^2 for radiant air flux. Compared to the simulations in which fuel was not placed on the sediment bed, the total peak flux measurements recorded at the soil surface and above the soil surface were considerably greater; however, radiant flux levels measured at the sediment surface significantly lower. This suggests that a greater proportion of the potential heat energy released during combustion was released away from the sediment surface. In effect, the fuels placed on the artifact bed provided a mitigating quality against direct flame contact and exposure to intense levels of radiant heat energy. Peak temperatures measured on the upper surfaces of artifacts ranged between 581-260.5°C with the majority of maximums falling with the 300-500°C range. The majority of peak lower surface temperatures ranged between 100-200°C with outlier values of 322.l°C and 38.2°C. These maximums are roughly analogous to those recorded during trials #10-12 with the exception that peak temperatures were attained over a period of 40-65 seconds compared to 20-30 seconds for the previous fuel absent trials. This is due to the added fuel placed on the sediment bed and above the experimental artifacts, which required additional time to combust fully. In essence, rate of heating and radiant heat exposure on the artifact bed were reduced by presence of fuel directly above. Temperature and heat flux data are presented in graphical form in Appendix 3, Figure 4.50 and Figure 4.51, data CD.

Consequently, the degree of significant thermal alteration observed during the simulation was limited compared to trials #10-12. The glass specimen exhibited one minor thermal fracture under thermal stress generated by peak upper and lower surface temperatures of 422.9°C and 43.5°C. The shell specimen sustained minor delamination on its interior surface, and the bone specimen exhibited enhanced surface cracking where weather-induced cracking had existed previously. Overall, thermal alteration of trial #22 experimental artifacts was limited to a heavy deposit of combustive residue on the exposed surfaces of all artifacts. This deposit was generally light brown in color and somewhat tacky in composition suggesting that the condensate tar deposit had not been completely combusted. Again, this is a result of placing fuel on artifacts during the simulation. Moreover, these fuels reduced the level of radiant heat energy that artifacts experienced and the rate at which artifacts were heated resulting in diminished thermal alteration.

Trial #23

Trial #23 was conducted as a replicate simulation under the moderate-light / low wind velocity (fuel on artifacts) experimental treatment. The results of this simulation were consistent with those reported for trial #22. Flaming combustion of excelsior fuels across the entire length of the burn table produced flames measuring 0.80m in height, 1.2m in length, and a flame angle of 47.3°. Combusting fuels placed on the artifact bed produced high total flux values of 45.5 kw/m^2 for total soil flux and 85.5 kw/m^2 for total air flux. Radiant flux at the sediment surface was relatively low at 17.0 kw/m^2, while radiant air flux remained consistent at 42.9 kw/m^2. These flux measurement suggest that a significant proportion of heat energy was released upwards and away form the sediment bed and artifacts. Peak temperatures measured on the upper surfaces of artifacts ranged between 400-500°C with outlying values of 556.6°C and 306.8°C. Maximum lower surface temperatures ranged between 225.0-47.12°C with most peak temperatures falling within the 100-200°C range. As observed for the previous trial, the presence of fuels on artifacts resulted in protracted peak heating intervals of 40-60 seconds and short residence times of 9-21 seconds. As a result, the rate of artifact heating was less dramatic than that observed during trials in which fuel on artifacts was absent. Graphical output of time / temperature and heat flux data from the simulation are provided in Appendix 3, Figure 4.52 and Figure 4.53, data CD.

Thermal alteration of experimental artifacts during trial #23 was consistent with that observed during the previous trial. All artifacts exhibited combustive residue deposits on exposed surfaces ranging from an adhesive yellow/brown to a more highly combusted glossy black. Significant thermal alteration of artifacts was limited to shell and bone specimens, which exhibited limited surface cracking. Peak upper surface temperatures recorded for these specimens were 424.4°C and 447.0°C. Partial combustion of the organic phase among shell, bone, and antler specimens was limited, resulting in minor weight reductions of 0.6-1.4%. Overall, thermal alteration of the experimental artifacts was characterized by combustive residue deposition. The presence of fuels on artifacts led to protracted heat-up rates and limited radiant heat energy output, which in turn, reduced the potential for significant thermal alteration of artifacts.

Trial #24

Trial #24 was the final replicate simulation conducted under the moderate-light fuel load / low wind velocity (fuel on artifacts) experimental treatment. The results of this replicate were generally consistent with that observed for the previous two trials with the exception of slightly greater flame dimensions and enhanced total air flux and peak upper surface temperatures. Maximum flames lengths and heights were measured at 1.5m and 1.0m respectively, at an angle of 42.0°. Based on the high total air flux measurement of 93.1 kw/m^2, the greatest proportion of heat energy generated during the simulation was released upwards and away from the sediment surface. This is supported further by the low peak radiant soil flux measurement of 9.3 kw/m^2 that was recorded during the trial. Peak temperatures measured by thermocouples placed on the upper surfaces of artifacts generally fell within the 400-500°C range, with some outlier values reaching the 600°C range. These temperatures reached apex levels within 40-65 seconds and were sustained for 8-20 seconds. Peak lower surface temperatures varied widely between 313.9-78.8°C; however, most maximum temperatures fell within the 100-200°C range. Time / temperature and heat flux data are provided in graphical form in Appendix 3, Figure 4.54 and Figure 4.55, data CD.

Thermal alteration of experimental artifacts during trial #24 was consistent with that observed during the previous two trials. Combustive residue deposits were pervasive across all exposed artifact surfaces, and ranged between an adhesive yellow/brown to deep glossy black depending on the extent of combustion of the condensate tar. Significant thermal alteration was limited to the shell and bone specimens, which sustained limited surface cracking under peak upper surface temperatures of 435.2-415.8°C. Partial combustion of shell, antler, and bone resulted in slight weight reductions of 1-2%. As reported for the previous two trials that were conducted under the same experimental treatment, the addition of fuel on artifacts protracted the heat-up rate experienced by artifacts and provided insulation against significant levels of radiant heat energy. Subsequently, the incidence of significant thermal damage to artifacts was more limited compared to the simulations where fuel was not placed on artifacts.

Light Fuel Load/Low Wind Velocity Condition (Trial #25)

One fire simulation, trial #25, was conducted under the light fuel load (1.00 ton/acre) (368.05/kg/ha), low wind velocity experimental condition. Based on the previous fire simulation performed using the same fuel load and a high wind velocity, limited heat output and artifact thermal alteration was predicted. Therefore, fire simulation under this experimental treatment was limited to one trial only.

Flaming combustion of lightly loaded fuels generated small flames measuring 0.64m in length and 0.46m in height, and the low wind velocity limited flame angle to 43.2°. Consequently, the heat energy generated during combustion was limited as well with peak measurements of 12.7 kw/m^2 for total soil flux, 6.0 kw/m^2 for radiant soil flux, 30.8 kw/m^2 for total air flux, and 13.2 kw/m^2 for radiant air flux. The elevated value of 30.8 3 kw/m^2 for total air flux suggests that a significant proportion of the heat energy generated during the simulation was released upwards into the atmosphere of the wind tunnel. This, combined with the fact the other flux measurements were low compared to other fire simulations using heavy fuel loadings is indicative of low fire severity. Peak temperatures measured on the upper surfaces of artifacts further support these empirical data. Maximum upper surface temperatures ranged between 319.6-113.4°C with most peaks falling within the 150-200°C range. Ascension to apexes for upper surface temperatures occurred quickly within 10-20 seconds and high temperatures were sustained only briefly for 4-8 seconds. Peak lower surface temperatures were also minimal with the majority of maximums falling within the 50-100°C range and outlier values of 163°C and 44.1°C. Time / temperature and heat flux data for trial #25 are summarized graphically in Appendix 3, Figure 4.56 and Figure 4.57, data CD.

The rapid but brief heating of artifacts combined with low heat energy output resulted in a very limited amount of thermal alteration of experimental artifacts. The only form of thermal alteration observed was a very light, almost transparent, combustive residue deposit on 10-20% of the exposed surface are of the artifacts. No significant thermal damage such as fracturing or surface cracking was observed. The light fuel load compounded by low wind velocity produced insufficient thermal energy to induce significant thermal alteration or heavy combustive residue deposits across the sample of artifacts.

Thermal Fracture Incidence among Experimental Artifacts

Following the completion of the wildland fire simulations, data from each simulation was analyzed to identify the trials in which thermal fracturing and other significant forms of thermal damage to experimental artifacts had occurred. Data was compiled for each specific artifact type to identify the temperature ranges at which thermal fracturing/damage had occurred. In addition, this section contains the methods and results the secondary TL dating and sandstone experiments. This information will aid in establishing the critical temperature ranges associated with the catastrophic thermal alteration of specific artifact types, and the wildland fire conditions under which significant thermal damage of specific archaeological resourced might occur.

Hartville Uplift Chert "Core"

Hartville Uplift chert nodules, roughly the size of expended cores, sustained the greatest degree of thermal fracturing of any of the materials burned during the wildland fire simulations. Ahler (1983) has demonstrated that cobble-sized pieces of Knife River flint are especially prone to thermal shock as compared to small performs or flakes. Thermal shock in brittle materials such as chert is caused by differential thermal stress induced during uneven heating of the material body (Luedtke 1992). Since the Hartville Uplift nodules were of notable size and thickness (~50x50x25mm) compared to a perform, biface or flaking debris, the potential for differential thermal stress induced during the fire simulations was greater for the core-sized specimens as compared to the other small-sized fine-grained lithic materials tested.

In total, nine Hartville Uplift chert specimens exhibited thermal fracturing, four exhibited linear surface cracking, three exhibited thermal spalling, and seven exhibited iron oxidation to hematite resulting in a color change from the original yellow-brown to dusky red. The mineral oxidation was generally observed on fragments displaced from the core body and/or within fracture scars on the main body. The color change is likely the result of limonite being oxidized to hematite where the mineralogy of the chert was affected during heating. Maximum temperatures measured by thermocouples placed on the upper surfaces of thermally fractured specimens ranged between 708.0-446.6°C. In general, peak upper surface temperatures ascended to apex levels within 40-60 seconds and were sustained at temperatures within 100°C of the peak value for an average of 20 seconds. Peak lower surface temperatures associated with fractured specimens ranged between 404.4-76.4°C, rising and falling more slowly and uniformly compared to upper surface temperature curves. The time/temperature data compiled for all thermally fractured specimens are quite similar for each specimen showing comparable curves for both upper and lower surface temperatures (Figure 4.58). The average peak upper surface temperature associated with thermal fracturing of the chert core was 546.8°C, and average peak lower surface temperature was 189.3°C. The average temperature differential between peak upper and lower surface temperatures was 66.5%. In sum, Hartville Uplift chert nodules are susceptible to thermal fracturing when their upper surfaces are precipitously heated to approximately 550°C for 20 seconds, and when the temperature differential between upper and lower surfaces approaches or exceeds 60%.

Thermal fracturing of the chert nodules was observed during wildland fire simulations using the 8.67, 6.33, and 4.34 fuel loadings paired with high wind velocity where flame angles were steep and upper artifact surface temperature elevated. This suggests that given sufficient fuel availability and burn intensity, larger sized chert artifacts deposited at soil surface are susceptible to thermal fracture during wildland fires under most fuel models except grassland.

In addition to thermal fracturing, chert core specimens also developed linear surface cracking, thermal spalling, and mineral oxidation resulting in pronounced color change during several of the fire simulations. Linear surface cracking was observed where the average peak upper surface temperature reached 414.9°C (near peak residence time of 20 seconds), and the average maximum lower surface temperature was 93.5°C; resulting in an average temperature differential of 77%. This suggests that linear surface cracking may precede complete thermal fracturing where fragments are physically detached from the main body since the linear cracking was observed under a lower peak upper and lower surface temperatures. Thermal cracking may ultimately lead to thermal fracturing given sufficient thermal stress to propagate the crack and form a complete fracture. Under field conditions this could potentially occur as the result of repeated exposure to multiple wildland fires. Thermal spalling occurred on the upper surfaces of the chert cores where the average peak upper surface temperature was 517.4°C with a residence time within 100°C of maximum for an average of 20 seconds. Mineral oxidation of individual fragments and within fracture scars on the main body of chert core specimens was also observed under an average maximum temperature of 517.4°C under sustained high temperature for an average of 19 seconds. These significant forms of thermal alteration were also generally observed during simulations using the 8.67, 6.33, and 4.34 fuel loading paired with high wind velocity. The only exception is the occurrence of linear surface cracking during two of the 6.33 fuel load / low wind velocity simulations, and the mineral oxidation and thermal spalling during two of the 8.67 fuel load / low wind velocity / fuel on artifacts simulations. Again, this suggests that these forms of thermal alteration occur during a variety of wildland fire scenarios given suitable conditions.

Pecos Chert Biface

Thermal fracturing of Pecos chert biface specimens was only observed during two of the fire simulations (Trial #2 and #8). In each of the simulations the specimens sustained complete linear (slightly undulating) fracturing at approximately the midpoint resulting in a clean fracture that somewhat resembled a snap fracture. These fractures occurred under extreme conditions where the average peak upper surface temperature for both specimens averaged 816.0°C, and the peak lower surface temperature averaged 293.8°C resulting in a temperature differential of 64%. Peak upper surface temperatures reached their apexes within 40-70 seconds, and temperatures above 800°C for sustained for five seconds with temperatures remaining in the 700-800°C range for 12-24 seconds. Time/temperature data for the two fractured specimens are very consistent, and are summarized graphically in Figure 4.59.

Compared to the larger Hartville Uplift chert "core" specimens, the Pecos chert bifaces appear to be more resistant to thermal fracturing. Thermal fracturing of the chert biface specimens was only observed under extreme thermal stress where peak upper surface temperatures were sustained above 800°C and the temperature differential between peak upper and lower surface temperatures was 64%. The small and uniform size of the biface specimens likely reduced the potential for catastrophic thermal stress within the material. Mandeville's (1973) heat treatment experiment has shown that thin chert materials such as flakes are less susceptible to thermal shock compared to larger chert artifact types. The rate of differential expansion within thin materials is potentially more equal where thin materials are concerned. The results of the fire simulations seem to support this assertion since the prevalence of thermal fracturing of chert biface specimens was relatively low, and only occurred under extreme thermal conditions generated by precipitous heating and elevated peak temperature. Interestingly, thermal fracturing of the chert biface specimens occurred during one of the high fuel load / high wind velocity simulations and during one of the moderate-light fuel load / high wind velocity simulations. Fracturing occurred independent of fuel loading, but only under extreme temperature gradient generated by large flame size and low flame angle. This suggests that although catastrophic thermal alteration of chert bifaces is probable only under extreme temperature, it may be observed under environmental conditions of variable fuel load and high fire severity.

Black Hills Quartzite Flake

Thermal fracturing of quartzite primary flakes was observed during six fire simulation trials, all of which occurred under the high wind velocity treatment, but at variable fuel loadings ranging from heavy to moderate-light. Peak upper surface temperatures associated with quartzite thermal fractures ranged between 650-433.5°C and averaged 565.3°C for the six specimens. These maximum temperatures reached apex levels within approximately 40-50 seconds and were sustained at elevated levels for 17-74 seconds. Maximum lower surface temperatures recorded for fractured specimens ranged between 593.1-143.0°C and averaged 277.4°C resulting in a 52% temperature differential average between upper and lower surface maximum temperatures. Four of the six thermal fractures occurred at the distal portion of the flakes where the material was thinnest. Mineral oxidation, resulting in a color alteration from brown to reddish-brown, was observed on fractured portions from four specimens and on the distal end of one non-fractured specimen. Again, this color alteration is likely due to the oxidation of iron minerals comprising the mineralogical composition of the quartzite. Maximum upper surface temperatures associated with mineral oxidation of Black Hills quartzite ranged between 613-433.5°C for an average of 528.8°C.

Archaeological literature surrounding the thermal alteration of lithic materials is generally focused on the heat treatment of chert as it applies to enhancing its flaking characteristics. Most of the literature addressing the thermal alteration of quartzite was located from geological sources. Thermal fracturing of quartzite follows the fundamental assumption applicable to most brittle materials, which is that when thermal stress exceeds the shear or tensile strength of a rock, elastic energy stored within the material is released and fracturing is propagated (Freeman et al. 1972; Marovelli et al. 1966). Important physical properties relevant to thermal fracturing of rock include; tensile strength, thermal diffusivity, thermal conductivity, and thermal expansivity (Freeman et al. 1972; Marovelli et al. 1966). Thermal expansivity of quartz reaches its maximum at 573°C when the alpha-beta transition occurs resulting in a change in crystal structure (Frondel 1962; Skinner 1966). Thus, at relatively low temperatures quartz undergoes a considerable thermal expansion, which may subsequently lead to thermal shock and fragmentation. Experiments conducted by Thirumalai (1970) have shown that quartzite is highly subject to spalling under thermal stress, and may occur at temperatures below the 573°C threshold. The results of the fire simulation experiments show consistent thermal fracturing of quartzite primary flakes at an average temperature of 565.3°C. When presented graphically in Figure (4.60), the time/temperature curves associated with thermally fractured specimens are very consistent. This suggests the thermal fracturing of quartzite artifacts is likely when subjected to precipitous heating beyond 550°C. Given that thermal fracturing of quartzite during the fire simulations occurred under three different fuel loadings, but only under high wind velocity, it is probable that thermal damage could occur under a variety of natural wildland fire scenarios where extreme fire conditions exist.

Obsidian Biface/Blade

Thermal fracturing of obsidian specimens was not observed during any of the wildland fire simulations, and the only significant form of thermal alteration observed consisted of the enhancement of radial fracture lines. These preexisting radial fracture lines were produced during knapping activities and generally consist of linear surface fractures originating from the point of initial percussion. Under thermal stress, these lines appear to increase in length, width, and presumably depth. No method of quantification was implemented to accurately measure the exact degree of fracture line augmentation, only subjective macroscopic analysis was used when assessing the presence of this form of thermal alteration. In total, enhanced radial fracture lines were observed on eleven specimens. The results from the fire simulation show that enhanced radial fracture lines formed during trials where the peak temperature measured on the upper surface of specimens were within the 500-600°C range or above (613.5°C average), and maximum lower surface temperatures were within the 150-300°C range (248.5°C average). In general, upper surface temperatures peaked within 40-50 seconds and were sustained within 100°C of maximum for 5-32 seconds. Lower surface temperatures peaked and fell in a more protracted and uniform manner. The temperature differential between peak upper and lower surface temperatures recorded for affected specimens was 60%. In addition to radial fracture line propagation, fine linear crazing (defined by Steffen 2002) was observed on the obsidian specimen from trial #1. Here the maximum upper surface temperature reached 814.0°C; however, this was the only incidence of crazing observed throughout the entire experiment. Figure (4.61) graphically summarizes the time/temperature data associated with specimens affected by radial fracture line enhancement, and with the exception of some outlier curves, the data are consistent.

These data suggest that where obsidian is subjected to precipitous and brief heating above 500°C, enhancement of radial fracture lines may develop. Again, this may potentially occur under a variety of wildland fire scenarios given sufficient fire intensity since it was observed in the laboratory under heavy to moderate light fuel loadings and at both high and low wind velocity. However, Nakazawa (2002) and Steffen (2002) have recorded a much wider range of thermal alteration of obsidian under laboratory experimentation and from archaeological contexts to include matte finish, surface sheen, fine crazing, deep surface cracking, vesiculation, incipient bubbles, and fire fracture (see Steffen 2002:163-165 for definitions). The major point of divergence between the wildland fire simulations and the laboratory experiments conducted by Nakazawa and Steffen is the length of time specimens were heated. During the wildland fire simulations burning was conducted on a burn table within the wind tunnel where fuel availability was limited to the predetermined g/m^2 loading. Flaming combustion during these simulations was rather brief, but analogous to many natural fire scenarios, and maximum temperatures were sustained for a maximum of 30-70 seconds. Steffen and Nakazawa heated obsidian in electric laboratory furnaces for minimum period of 1 hour up to 12 hours. Clearly, the longer duration of heating during these experiments created an increased probability to a wider range of thermal alteration to occur. Steffen has also observed significant thermal alteration of obsidian at a large quarry site burned by a wildland fire in New Mexico (1996 Dome Fire). The degree of thermal alteration observed was dependent on fire severity. The most extreme examples of thermal alteration were probably observed from contexts where heavy fuels burned intensely for long durations during the fire; for example, where logs or heavy litter were combusted in close proximity of obsidian artifacts deposited at the soil surface. The limitations of wildland fire simulations in a laboratory setting prevented the experiment from replicating scenarios where logs, stumps, and heavy litter burn over a long duration. Nonetheless, the results of the fire simulations show that brief heating in excess of 500°C will induce radial fracture line propagation, and given, longer burn durations, a wider range of thermal alteration would have likely been observed. In addition the effects of wildland and prescribed fire on obsidian artifacts is not limited to thermal damage alone. There are significant implications surrounding the effect of heating on hydration bands and the geochemical structure of thermally altered obsidian that could potentially lead to inaccurate obsidian dating and sourcing. Although this issue is beyond the scope of the present study, several researchers have conducted relevant research concerning this issue (Benson 2002; Deal 2002; Origer 1996; Shackley and Dillian 2002; Skinner 2002; Steffen 2002; Trembour 1990).

Bottle Glass

Like other brittle materials, glass will fracture when thermal energy generates internal stresses that exceed the tensile strength threshold of the material (DeHaan 1997; Lentini 1992). Glass, depending on its composition, also has an established melting point of approximately 700-800°C (DeHann 1997:446). Thermal fracturing of bottle glass specimens was observed during ten fire simulations. The most significant fracturing occurred during two of the heavy fuel load / high wind velocity trials where specimens were severely fractured into 15-22 individual fragments. The peak upper surface temperatures associated with these two specimens were 888.0°C and 586.8°C, which were sustained for prolonged periods of 54-59 seconds, and the temperature differential between maximum upper and lower surface temperatures of greater than 90%. The majority of glass fractures occurred where peak upper surface temperatures were within the 400-500°C range for an average temperature of 534.2°C. Maximum lower surface temperatures averaged only 99.4°C for an average temperature differential between maximum upper and lower surface temperatures of

78.8%. Time/temperature data associated with fractured glass are summarized in Figure (4.62). These results suggest that thermal fracturing of bottle glass is initiated by precipitous heating to at least 400°C. Thermal fracturing was observed under most fuel loadings except low, and under both high and low wind velocity conditions. Thus, it is likely that thermal fracturing of glass will occur under a wide variety of prescribed and wildland fire scenarios, with the possible exception of grassland fires.

Bone, Antler, Shell

Several researchers have documented processes involved in the thermal alteration of bone, although generally not with the intent of addressing the impact of natural fire on archaeological bone (Bennett 1999; Bonucci and Graziani 1975; Bradtmiller and Buikstra 1984; Brain 1993; Buikstra ad Swegle 1989; Herrmann 1977; Kizzely 1973; McCutcheon 1992; Nicholson 1993; Shipman et al. 1984; Sillen and Hoering 1993; Stiner et al. 1995; Von Endt and Ortner 1984). Nonetheless, the information provided by these researchers is quite useful in developing an understanding of how heat affects organic materials such as bone, antler, and shell. Significant thermal alteration of organic specimens (bone, antler, and shell) was observed during each to the fire simulations with exception of the light fuel load trials. Thermal alteration of bone specimens was generally characterized by charring and partial combustion of upper exposed surfaces, the propagation of existing surface cracks, and combustion of the organic phase resulting in mass reductions of 2.4-4.3%. In addition, bone specimens were noticeably more brittle upon handling after the fire simulations; however, no quantitative method was used to accurately measure the degree of increased friability caused by heating. Thermal alteration was most pronounced during the high wind velocity simulations where heavy and moderate fuel loadings were used (peak upper surface temperatures 300-600°C). The degree of friability, crack propagation, and combustion of the organic phase for bone specimens diminished in severity as burn intensity diminished under lighter fuel loads and lower wind velocities. Thermal alteration of elk antler specimens was generally limited to charring of upper surfaces and partial combustion resulting in weight loss. Weight reductions ranged between 1.6-5.0%. Again, the degree of charring and mass reduction was linked to the severity of each respective fire simulation. No thermal fractures or appreciable increase in preexisting surface cracks was observed for antler specimens. Thermal alteration of shell specimens included delamination of interior surfaces, linear cracking, increased friability, and mass loss. These forms of thermal alteration were also most pronounced during high intensity fire simulations. Figure (4.63) summarizes the mass reductions experienced by organic specimens. The chart shows a that mass reduction is consistently diminished as fuel load / fire severity is decreased. In sum, significant thermal alteration of organic specimens is likely to occur under most prescribed and wildland fire scenarios with the possible exception of grassland fires.

Cliff House Formation Sandstone Block Sections

Thermal alteration of Cliff House Formation sandstone block sections from Mesa Verde National Park was very limited. Aside from light to moderate combustive residue deposition, the only significant form of thermal alteration observed was a minimal degree of oxidation along the leading edges on the upper surfaces of eight specimens. The oxidation was observed as a dusky red linear streak extending along the upper edge of affected specimens where heat exposure was sufficient to induce mineral oxidation. The unheated color of the sandstone is yellowish-brown, which when heated to sufficient temperature will oxidize to a dusky red color. This color alteration occurs when limonite (FeO(OH)) oxidizes to a more stable hematite (Fe_2O_3) (Philip Cloues personal communication 2003). The results of the fire simulations show that the oxidation process is initiated at approximately 300°C.

The average peak upper surface temperature recorded for the eight affected specimens was 410.9°C, and aside from two high outlier values, the majority of generated time/temperature curves consistently peak in the 300°C range (Figure 4.64). Oxidation was observed during simulations using the heavy, moderate, and moderate light fuel loadings, but only under the high wind velocity treatment.

The extent of oxidation observed during the laboratory fire simulations was negligible compared to that observed in the field at Ancestral Pueblo sites within Mesa Verde National Park that had been subjected to severe wildland fire conditions (see Chapter 5 for a discussion). Again, the major distinction between that observed in the field and that observed in the laboratory is duration of heating, and the number of heating events that affect the archaeological materials. During the laboratory fire simulations peak temperatures were sustained for a brief period, generally 10-70 seconds. It is apparent that these brief residence times, compounded by the position of the sandstone specimens at the far end of the sediment bed (38cm from fuels), are responsible to the limited degree of oxidation observed during the simulations. Clearly, a longer duration of heating is required to produce pervasive oxidation of Cliff House Formation sandstone. During the fire effects project conducted at Mesa Verde, heavy fuels were often recorded in association with pronounced oxidation of architectural elements. The wildland fire simulation performed at the IFSL where, however, insufficient to replicate the extreme fire conditions affecting archaeological sites at Mesa Verde. In order address this issue, a new experimental design was developed and implemented independent of the IFSL experiment.

<u>Secondary Cliff House Formation Sandstone Thermal Alteration Experiment</u>

The secondary experiment was implemented to replicate the degree of thermal alteration of Cliff House Formation sandstone architectural elements observed during fire effects sampling project at Mesa Verde National Park (Figure 4.65). In the field, oxidation, thermal spalling and thermal fracturing was observed at varying degrees depending on fire severity. As discussed above, oxidation of this particular type of sandstone is characterized by a color shift from yellow-brown to dusky red due to the oxidation of iron minerals. Important variables relevant to thermal fracturing and spalling of sedimentary rock include; temperature; duration of heating, steam pressure (water content), tensile strength, thermal diffusivity, thermal conductivity, and thermal expansivity (Freeman et al. 1972; Hettema et al. 1998; Marovelli et al. 1966; Wai et al. 1982). Thermal fracturing of sedimentary rock has been shown to initiate through a fracture mechanism in which thermally induced stress exceeds the shear or tensile strength of the rock (Hettema et al. 1998; Freeman et al. 1972; Wai et al. 1982; Williams et al. 1996). Hettema et al. (1998) have empirically demonstrated that steam pressure and fracture mechanisms generated by compressive thermal stress are the primary forces that initiate thermal spalling in sedimentary rock.

The present experiment consisted of a simplified design in which Cliff House Formation Sandstone specimens were heated using a high volume (500,000 BTU) propane vapor torch (Red Dragon Torch, Flame Engineering Inc.). The use of the torch allowed sandstone specimens to be heated more uniformly and for a longer duration than that achieved during the IFSL fire simulations. Temperature was recorded at one-second intervals using an Omega OM-3000 portable data logger and six Type K hi-temperature inconel overbraided ceramic fiber insulated thermocouples (XCIB-K-1-2-25, 25ft length, Type OST male connector, probe style 1 termination) (Omega Engineering 2000). Each specimen was drilled with 3 holes (6mm dia.) in a linear orientation and at 5cm intervals. The holes allowed three thermocouples to be positioned flush with the upper surface of each specimen in order to record time/temperature data across the upper surface of the sandstone.

The experiment was conducted in an outdoor area on a 60x80 sediment bed (sand matrix) constructed of brick. The torch was placed in a horizontal position 6cm above the sediment bed such that the upper surface of each sandstone specimen was on a horizontal plane with the head of the propane torch. Actuating the gas flow valve on the torch and varying the distance between the torch head and the sandstone specimen controlled heat intensity during the experiment. Three wildland fire intensities were simulated, Light (valve 50% open, 20cm from torch), Moderate (valve 50% open, 15cm from torch), Severe (valve 75% open, 15cm from torch). Under each condition, specimens were heated for four minutes. Each condition was replicated three times, including a total of nine specimens. Information on temperature and observable thermal alteration were noted during each trial at 30 intervals, and post-heating once cooling was complete.

The results of the light severity trials show that peak surface temperatures during the trials ranged between 361-339°C. During each trial, oxidation was observed to initiate at temperatures between 200-300°C. Oxidation was observed on approximately 40% of the upper surface of each specimen, and at depths ranging between 1-15mm (deepest oxidation on portion of stone nearest to the torch). Minor thermal spalling was also observed on the leading edge of each specimen where temperatures were maintained in the 200-300°C for approximately 2 minutes. Two spalls were observed for each specimen. Thermal spalling was initiated by the formation of fine surface cracks in the outline of a spall followed by exfoliation after heating was terminated.

Peak surface temperatures during the moderate severity trials ranged between 515-688°C. The results of these heating trials confirm that oxidation and minor thermal spalling of Cliff House Formation sandstone is initiated at 200-300°C, but also demonstrate that oxidation and thermal spalling become more pervasive as temperatures are sustained in the

400-500°C range for durations of approximately two minutes. In addition, the initiation of thermal fracturing in the form of linear surface cracking was also observed in this temperature range. Post-heating analysis of each specimen showed the presence of oxidation on 50-60% of upper surfaces, thermal spalling (2-4 spalls), and linear surface cracking.

The results of the severe trials show that peak surface temperatures during heating ranged between 612-726°C. Observations recorded during these trials are consistent with those recorded during the light and moderate heating trails in which oxidation and minor thermal spalling was observed to develop at temperatures of 200-300°C. Similar to that observed during the moderate trial, increased oxidation, thermal spalling, and the initiation of thermal fractures was also observed at temperatures between 400-500°C during the severe heating trials. In addition, pervasive oxidation, thermal spalling, and thermal fracturing were observed as temperatures were sustained in the 500-700°C for approximately 2 minutes during the severe heating trials. Post-heating, oxidation was observed on 90% of the upper surface area of each specimen and at depths of up to 30mm. Each specimen also exhibited 5-6 large spalls (70-100mm in dia.), multiple linear thermal fractures, and 1-4 detached fragments resulting from thermal fractures.

Overall, the experiment was successful in replicating the range of thermal alteration observed on architectural rubble from Ancestral Pueblo sites burned by wildland fire at Mesa Verde National Park. Figure (4.66) shows the range of thermal alteration of sandstone specimens generated during the experiment. In brief, the results of the experiment demonstrate the thermal of Cliff House Formation Sandstone can be summarized as follows:

200-300°C Initiation of light oxidation and minor thermal spalling

300-400°C Initiation of thermal spalling and increased oxidation (surface area)

400-500°C Prominent oxidation (increased surface area and depth), increased thermal spalling, initiation of linear thermal fractures.

500-700°C Pervasive oxidation (increased surface area and depth), pervasive thermal spalling and fracturing.

Secondary Thermoluminescence Dating Experiment

The purpose of the thermoluminescence (TL) ancillary experiment was to assess the potential impact of variable wildland fire intensities on the TL signal for prehistoric pottery sherds. TL dating of pottery is based on the accumulation of radioactive elements in the crystalline structure of pottery that decay at a known rate (Aitken 1985; Feathers 2000). Over time, radioactive decay causes the ionization of atoms that become trapped at points of imperfection in the crystal lattice. When heated, the charge from trapped electrons is released resulting in a TL signal that is proportional to the period of time since the material was last heated, which generally relates to the time that the pottery was originally fired during manufacture. Luminescence signals in pottery are generally not affected by heating where the temperature is less than 250°C (Aitken 1985). Theoretically, TL signals for sherds burned during wildland fires could be altered or zeroed if the sherd was sufficiently heated. Rowlett (1991) and Rowlett and Johannessen (1990) have generated preliminary evidence that demonstrates that wildland fire can alter the TL signal for pottery sherds; however, additional research is needed to augment their findings.

Experimental Method

The TL experiment was run in conjunction with the primary wildland fire simulation experiment conducted at the IFSL. Pottery sherds to be submitted for TL analysis were subjected to variable fire intensities (Low, Moderate, High) during three of the wildland fire simulations (Trial #6, Trial #12, and Trial #26) performed at the lab. The experimental specimens were derived from two sherds, one unknown prehistoric sherd from northeast

Kansas, and one corrugated Pueblo sherd from southwest Colorado. The specimens were attained from museum collections and have no specific typological or provenance data. Each of the sherds was divided into 4 pieces (~3cm dia.), producing a total of 8 individual samples. One sample was created to represent the control sample. Sample set #2 was heated under a low intensity wildland fire condition. Sample set #3 was heated under moderate fire intensity, and sample set #4 was burned under a high intensity experimental condition. Time and temperature data were recorded using the same method used for the primary IFSL experiment (thermocouple placement on the upper and lower surfaces of specimens). Post-heating, the samples were sent to James Feathers at the University of Washington Thermoluminescence Dating Laboratory for analysis.

The procedures used in the study to derive TL signals from the sample sherds are described in detail in Appendix 3 located on the data CD. In brief, a luminescence age is obtained through the following equation (Feathers 2003 Personal Communication):

$$\text{Age (t)} = \text{De (Gy)} / \text{Dr (Gy/t)}$$

Where t is a unit of time, De is the equivalent dose, Dr is the dose rate, and Gy is the international unit for adsorbed radiation dose. De is sometimes called the paleodose and represents the accumulated dose in the potter since it was last exposed to sufficient heat. Any significant reheating of the pottery after the heating of interest (when the ceramic was made or used) will cause a reduction in De. Dr is obtained from the natural radioactivity of the sherd and its immediate environment. It is usually assumed to be constant since time of deposition and is not affected by reheating. Dr is composed of an internal (from within the sherd) and an external (immediate environment) component. The latter normally constitutes about a fourth to a third of the total dose rate. Because the external component in this study is unknown, accurate dates for the two sherds cannot be obtained, although approximations con be employed to arrive at some reasonable estimate.

De is determined by measuring the natural luminescence signal from either coarse or fine grains from the sherd and calibrating that signal against known laboratory irradiation. Fine grains were used in this study. Two general ways of measuring luminescence are through stimulation by heat (thermoluminescence, TL) or by light, either in the visible range (optically stimulated luminescence, OSL) or in the infrared region (infrared stimulated luminescence IRSL). All three methods were employed in this study.

The results of the TL analysis summarized in the following section were provided by Feathers (2003). The results of the experiment show that there is a substantial differential in temperature gradient between the upper lower surfaces of the sherds and that the sherds were not exposed to temperatures inimical to luminescence dating (Table 4.2).

Table 4.2: Summary of sample heating from wildland fire simulations.

Sample	Thermocouple placement	Seconds exposed to temperature (°C)						
		>800	>700	>600	>500	>400	>300	>200
		Low Fire Intensity						
Kansas	Upper	0	0	0	0	0	8	17
	Lower	0	0	0	0	0	0	0
Puebloan	Upper	0	0	0	0	0	0	10
	Lower	0	0	0	0	0	0	0
		Medium Fire Intensity						
Kansas	Upper	0	0	1	12	18	24	32
	Lower	0	0	0	0	0	0	13
Puebloan	Upper	0	0	0	0	0	17	29
	Lower	0	0	0	0	0	0	0
		High Fire Intensity						
Kansas	Upper	0	1	38	45	50	56	75
	Lower	0	0	0	0	0	0	2
Puebloan	Upper	0	0	0	0	21	37	56
	Lower	0	0	0	0	0	0	0

Sample material for dating are extracted at least 2mm from any surface, thus it is unlikely that the Low heating condition for either sherd or the moderately heated Pueblo sherd had any adverse effects within the TL sampling window of the sherd.

Dr was only measured on the unheated control specimens and on the medium- fired Kansas specimen. Table 4.3 gives the radioactivity of the three main components. There was some variation between the Kansas control and the Kansas medium- fired piece, which is somewhat surprising given both originated from the same pot, but this difference yielded a difference in age for the sample of only about 30 years, so it is not considered significant. The U and Th contents of the Puebloan sherd were unusually high, although not far outside the range typical for Southwestern pottery. The external dose rate was estimated to be 0.5 ± 0.25 of the pottery dose rate. Surrounding sediments are generally lower in radioactivity than the clay-rich ceramics, and if either sherd came from the surface or near the surface, the external dose rate would be reduced even more. Cosmic radiation, whose contribution to the dose rate is just significant, was estimated for typical locations in Colorado or Kansas.

Table 4.3 Radioactivity components of sample sherds.

Sample	^{238}U (ppm)	^{232}Th (ppm)	K (%)
Kanasa control	5.91±0.34	8.39±1.21	2.09±0.03
Kansas medium fired	6.61±0.40	11.51±1.58	2.01±0.01
Puebloan control	9.42±0.61	26.06±2.47	1.08±0.03

In measuring De by TL, one requirement is to establish a temperature range over which the luminescence signal is stable. This ensures that the signal has not been reduced (or faded) over time. This is generally done by means of a plateau test, which plots TL signal against temperature. A broad plateau in the range 250-400°C is desirable, although the dating is perfectly feasible with plateaus as short as 50-60°C in length. If the sample has been reheated to about 300-400°C, one might expect a truncated plateau or no plateau at all. A truncated plateau could take the form of two plateaus, a higher one corresponding to the original heating and a lower one corresponding to the reheating. For reheating beyond 400-500°C, one might expect the establishment of an entirely new plateau at a lower De. Table 4.4 gives plateau data for the two sherds. Plateaus are broad for both sherds in unheated, low-fired and medium-fired categories, suggesting none of these firing regimes have affected the luminescence. The high-fired plateaus are shorter, as might be expected, but still broad enough that dates could be obtained.

Table 4.4 Plateau data for samples.

Sample	Plateau (°C)
Kansas	
Unheated	250-390
Low-fired	240-360
Medium-fired	250-410
High-fired	320-370
Puebloan	
Unheated	280-370
Low-fired	270-400
Medium-fired	250-370
High-fired	310-360

Each of the samples showed sensitivity change with the second glow regeneration curve, more so for the control samples than the others. All the fits were linear, except for the high-fired Puebloan sample for which the data were better fit by a quadratic function. Equivalent dose for IRSL and OSL were determined by the SAR method (see appendix) on single aliquots. (No IRSL or OSL data are available yet for the Kansas unheated control sample because the original material had been exhausted and additional material not yet obtained.) IRSL was measured first, followed by a high-temperature (200°C, 5-minutes) wash, and then the OSL was measured. Only feldspars are sensitive to IRSL, so the idea behind measuring IRSL first (and including the high temperature wash) is to remove the feldspar signal. The OSL signal, measured using blue light, then derives primarily from quartz. Influence from feldspar may not be entirely eliminated, since it too is sensitive to blue light stimulation, but it should be reduced. The purpose of separating the feldspar and quartz signals is because feldspar suffers from what is called anomalous fading, or the reduction through time of signal that should on kinetic grounds be stable. Fading will affect the IRSL signal but to a lesser extent, if at all, the OSL signal. TL, measured on polymineral fractions, will also be affected by anomalous fading. Table (4.5) gives the De derived from the various methods, and the b-value, which is the ratio of additive dose slopes using beta and alpha irradiation. This is used to correct for the lower efficiency of alpha irradiation in producing luminescence. The values are broadly similar among different sub-samples of the same sherd, but with perhaps more variation than might be expected.

Table 4.5 De sample derived for each TL method.

Sample	De (Gy)			b-value
	TL	IRSL	OSL	(Gy μm^2)
		Kansas sherd		
Unheated	1.82±0.26			1.36±0.08
Low	2.97±0.24	4.60±1.31	8.49±0.16	1.49±0.12
Moderate	4.74±0.44	4.03±0.19	3.98±0.17	1.00±0.07
High	1.91±0.20	3.45±0.18	3.96±0.08	1.19±0.06
		Puebloan sherd		
Unheated	2.83±0.27	4.52±0.30	4.79±0.66	1.20±0.12
Low	3.67±0.24	4.57±0.16	5.02±0.19	1.42±0.10
Moderate	3.74±0.55*	5.17±0.41	4.88±0.43	1.55±0.22
High	3.97±0.55	4.24±0.25	5.16±0.33	0.52±0.06

*Determined from only the 250-290°C portion of the plateau region because of reduced error.

Consider the IRSL and OSL data first. For the Puebloan sherd there is good consistency across all firing regimes and between IRSL and OSL. This is strong evidence that the firing had no influence on either signal. The agreement between IRSL and OSL suggests no anomalous fading. The Kansas results (ignoring the fact that the unheated sample has not been measured yet) reflect the same consistency as is apparent for the Pueblo sample except for an anomalously high value for the low-fired sample. Disregarding this high value, for which no explanation is given, no evidence for any firing effect or fading is apparent for this sherd either.

The TL results, on the other hand, do not have the same consistency across heating conditions, and they are systematically lower than those from IRSL and OSL. The lack of consistency might reflect errors in correcting for sensitivity change. That such errors might be substantial is apparent from the b-value data, which are more variable than they should be. Calculation of the b-value uses the same computer fitting program as the slide technique does. Also, determining the equivalent dose from additive dose alone (data not shown) produces more consistent results. The systematic underestimation is harder to explain. The difference between TL and OSL might be attributed to anomalous fading, but the IRSL suggests no fading – unless it is manifested in the TL but not the IRSL. This does not seem likely, but a direct test for anomalous fading for both IR and TL is underway.

Using the approximations for external dose rate, rough ages for the two sherds can be obtained (Table 4.6). The OSL ages appear more realistic, providing further evidence the TL De's are in error.

Table 4.6 Rough age estimates for each sherd.

Sample	Age (years A.D.)	
	TL	OSL
Puebloan	1625±50	1360±100
Kansas (De = 4.0)	1660±55	1260±50
Kansas (De = 8.5)		420±85

Despite the uncomfortable discrepancy between De's obtained from TL and IRSL/OSL, no evidence is apparent that any of the heating conditions employed during the fire simulations had any serious effect on luminescence dating.

The wildland fire simulations did not generate sufficient periods of high energy prolonged heating necessary to significantly affect or zero the TL signal of the sampled sherds. It is clear that there was a significant temperature differential between the upper and lower surfaces of a sherd as a flame front passed over during the fire simulations. The heat energy radiated to the upper surface of sherds during wildland fire must be sufficient to conduct thermal energy through the sherd such that TL sampling window of the sherd is heated in excess of 250°C for an extended duration. If TL signals from pottery sherds located at or near the soil surface during wildland fires are to be significantly affected, large fuels capable of sustaining high levels of radiant heat energy must be present during combustion. Cleary, additional research is needed to establish the parameters under which TL signals are negatively affected as the result of natural fire. The results of this study do, however, suggest that the TL signal of sherds may not be significantly affected during low-level wildland and prescribed fire scenarios. This is encouraging for land managers and researchers confronted with preservation concerns or research validity issues that could be confounded due to wildland or prescribed fire.

SUMMARY AND CONCLUSIONS

In conclusion, the results of the fire simulations have shown that the most severe temperature gradients and greatest degree of artifact thermal alteration occurred during trials conducted under the high wind velocity treatment. Summary data for each of the experimental trials are provided in Table 4.7. The most severe heating and thermal damage occurred during trials #1-3 where high wind velocity (5-6 mph) was paired with a heavy fuel load of 8.67 ton/acre. Precipitous heating to the 500-800°C range induced thermal fracturing in chert, quartzite, and glass specimens as well as producing deep charring, surface cracking, and mass loss among organic specimens. During trials conducted under the moderate 6.33 ton/acre fuel load and high wind velocity treatment, peak temperatures measured on the upper surfaces of artifacts were generally within the 400-700°C range. Thermal fracturing was observed for various quartzite, chert, and glass specimens, albeit to a lesser degree than that observed during the heavy fuel load / high wind velocity fire simulations. Thermal alteration of organic specimens remained consistent with the exception of a slight reduction in the degree of mass loss associated with partial combustion. This trend continued during the moderate-light 4.34 ton/acre fuel load / high wind velocity fire simulations. Here peak temperatures measured on the upper surfaces of artifacts generally were between the 400-600°C with the exception of some anomalous 700-800°C values recorded during trial #8. Thermal fracturing was most consistent for the chert cores specimens with limited fracturing observed for quartzite and glass specimens. However, during trial #8 where the peak temperature associated with the Pecos chert biface, thermal fracturing was also observed for that specimen. Organic specimens exhibited charring, surface damage, and a reduction in mass loss associated with partial combustion.

These data and those presented in the previous sections suggest that the two most important variables affecting thermally damaged archaeological materials are fuel load and wind velocity. The degree of artifact thermal alteration observed during each set of fire simulations (heavy, moderate, moderate-light fuel loadings) was diminished only slightly as fuel load was lessened. This suggests that: 1) Fuel load is an important variable that affects the amount of potential energy that can be released during a wildland or prescribed fire; and 2) Wind velocity is also an important factor in determining fire severity as it pertains to the amount of thermal energy that is released at the sediment surface. During the high wind velocity simulations, flame angles were generally steep, routinely measuring in excess of 50°. This in effect, produced an enhanced potential for high levels of heat energy to be released at the sediment surface even when the fuel loading was reduced. These observations suggest that under severe fire conditions, a significant degree of thermal damage to surface archaeological materials can be expected in various natural environments ranging from mixed conifer to piñon-juniper to sagebrush. The only possible exception to this assumption is natural fire in grassland environments. The fire simulations using a 1.00 ton/acre fuel load paired with a high wind velocity produced only a limited degree of artifact thermal alteration, namely a light deposit of combustive residue. Peak temperatures here were generally limited to the 300-400°C range and were sustained for only a brief period of 4-10 seconds. These data suggest the prospective for significant thermal damage to surface artifacts during grassland fires is limited by light fuel load and low potential heat energy output.

When the fire simulations where performed using the same four fuel loadings, but paired low wind velocity of 2-3 mph, the relationship between these two variables as they affect the degree of observable thermal alteration of experimental artifacts was reiterated. Again, the greatest proportion of thermally damaged artifacts was associated with the heavy fuel load treatment; however, the extent of thermal alteration was diminished compared to trials conduced under the high wind velocity treatment. Here, peak temperature measured on the upper surfaces of artifacts generally fell within the 400-500°C range. Moreover, significant thermal damage was limited to one chert core specimen, one glass specimen, and limited charring and partial combustion of organics. This trend of reduced fire intensity under the low wind velocity treatment continued during the moderate 6.33ton/acre fuel load simulations. During these trials, maximum temperatures measured on the upper surfaces of artifacts generally were within the 300-500°C range and significant thermal damage to experimental artifacts was limited to the chert core specimens and to a lesser extent the organic specimens. This trend continued during simulations where the fuel load was reduced to 4.34 ton/acre. Here peak temperatures measured on the upper surfaces of artifacts were consistently in the 400-500°C range, and thermal damage was limited to two glass specimens and organic specimens. The 1.00 fuel load / low wind velocity simulation produced low peak temperatures of short duration, and essentially no significant thermal alteration of the experimental artifacts. The results of low wind velocity simulations reiterate the importance of fuel load as it pertains to potential heat energy output and resultant thermal alteration of archaeological materials; however they also suggest that reduced flame angle (<45°) under lower wind velocity limits the amount of potential heat energy emitted to artifact surfaces, which in turn, reduced the potential for significant thermal damage of those artifacts.

This observation is supported further when the heat flux data for these fire simulations are considered. Peak total air flux reading for these simulations where consistently high, often measuring in excess of 80 kw/m^2, which suggests that due to reduced flame angle a large proportion of heat energy was emitted upwards, away from artifact surfaces. Therefore, under less severe wildland fire conditions, the potential for significant thermal damage of surface archaeological materials is not as likely compared to high severity fire conditions under various fuel loads. Where fire intensity is low to moderate, fuel load is the most important variable affecting the potential for significant thermal alteration of archaeological resources.

Two simulations were conducted in which fuel was placed on the experimental artifacts to simulate natural conditions where duff and light litter may be present above the mineral soil surface and archaeological materials deposited there. During the heavy fuel load (8.67 ton/acre) / low wind velocity / fuel on artifacts trials, maximum temperature measured on the upper surface of artifact generally fell within the 400-600°C range. However, peak temperatures were attained over a protracted period of 75-200 seconds, producing more gradual and uniform temperature gradients. As a result, the degree of thermal alteration observed on experimental artifacts was considerably less severe compared to the other heavy fuel load fire simulations. Thermal alteration was generally limited to heavy combustive residue deposition, and limited thermal spalling of two chert core specimens. This trend was continued during fire simulations conducted using a 4.34 ton/acre fuel load, low wind velocity, and fuel placement on artifact. Here maximum temperatures measured on the upper surfaces of artifact consistently fell within the 300-500° range, but under more uniform and gradual temperature gradients as compared to comparable simulations where fuel was not present on artifact surfaces. Here, heavy combustive residue deposition on exposed artifact surfaces was also observed, and the significant thermal alteration was limited to only one glass specimen. The results of these simulations suggest that where duff is present in the layers above archaeological materials in natural environments, the potential for significant thermal alteration may be somewhat mitigated. Although, peak temperatures recorded during these simulations were likely sufficient to induce thermal shock, the rate at which the heating occurred reduced its potential. Thus, in wildland fire scenarios where a duff layer mitigates direct flame contact with archaeological materials, the potential for significant thermal damage is reduced. The only exception to this assertion would likely be scenarios where heavy litter or downed logs are present above the duff layer.

Concerning the impact of wildland and prescribed fire on specific artifact classes, it is clear that among the material types tested during the wildland fire simulation project large-sized chert nodules, quartzite primary flakes, glass, organic specimens, and to a lesser degree chert bifaces, are most susceptible to thermal damage. The Hartville Uplift chert nodules sustained significant thermal alteration in the form of thermal fracturing, thermal spalling, potlid fracturing, and mineral oxidation during several of the wildland fire simulations, particularly those conducted under the heavy, moderate, and moderate-light fuel loadings paired with a high wind velocity. These forms of thermal damage were consistently observed where the upper surfaces of specimens were precipitously heated to approximately 550°C for 20 seconds, and where the differential between peak upper and lower surface temperatures approached 60%. Similarly, significant thermal alteration of Black Hills quartzite primary flakes in the form of thermal fractures and mineral oxidation was observed at peak upper surface temperatures of approximately 560°C (sustained within 100°C of maximum for 40-50 seconds), and where the peak upper/lower surface temperature differential was approximately 52%. These conditions occurred under heavy, moderate, and moderate-light fuel loads, but only where the wind velocity condition was maintained at the 6 mph level. Glass specimens exhibited thermal fracturing where peak upper surface temperatures averaged approximately 530°C, and the temperature differential between maximum upper and lower surface temperatures averaged approximately 78%. Thermal fracturing of glass also occurred under most fuel loadings except the light (1.00 ton/acre) as well as under both low and high wind velocities. Significant thermal alteration of bone, antler, and shell in the form of charring, partial combustion, and surface cracking/exfoliation occurred during all experimental treatments with the exception of the light fuel load simulations. However, the degree of thermal alteration of organics is largely dependent on fuel load and fire intensity whereby the most severe thermal damage increased incrementally as fuel load and fire intensity increases. Moreover, heating of these material renders them considerably more friable, which may have significant implications for the preservation of archaeological organics post-fire.

Other material types for which significant thermal alteration was more limited include obsidian, sandstone, pottery sherds, and chert biface specimens. No significant thermal damage in the form of thermal fracturing or spalling was observed for Southwestern black-on-white and corrugated pottery sherd specimens. Although these forms of thermal damage were observed in field contexts during the Mesa Verde fire effects project (Chapter 5), the laboratory fire simulations were insufficient to induce thermal fracturing or spalling. The original manufacture and use of the artifacts by Ancestral Pueblo peoples involved exposure to heat; therefore, simply by nature of design, these materials are likely to be resistant to thermal stress generated by wildland or prescribed fire. One exception, however, would include combustive residue deposits that may obscure diagnostic features. It is also possible that post-depositional heating during wildland fires may have implications for accurate thermoluminescence dating of pottery sherds given sufficient fire intensity and heating duration. Obsidian biface and blade specimens exhibited the propagation of existing radial fracture lines under thermal stress induced by peak upper surface temperatures of approximately 610°C for a duration of less than 30 seconds, and where the differential between peak upper and lower surface temperatures was approximately 60%. This generally occurred under during high severity fire simulations. Thermal alteration of the Cliff House Formation during the fire simulations was very limited, generally consisting of only a thin linear red band where the oxidation of iron minerals was initiated. This occurred under peak temperatures of 300°C and above; however, given the short duration of flaming combustion during the simulations the thermal alteration was not nearly as pronounced as that observed in the field during the Mesa Verde fire effects project (Chapter 5) (see also Cliff House Formation Sandstone section of this chapter for additional experimentation where these conditions where successfully replicated). Significant thermal alteration of Pecos chert biface specimens in the form of complete fractures through the midsection was only observed during two fire simulations where peak upper surface temperatures exceeded 800°C. Nonetheless, the results suggest that catastrophic thermal alteration of small, more uniform chert artifacts is likely given sufficient fire severity and temperature gradient.

In sum, results of the laboratory wildland fire simulation have demonstrated that significant thermal alteration of a variety of archaeological material types can occur under various wildland fire scenarios. In general, the greatest degree of thermal alteration is, quite simply, strongly linked with high fire severity. However, severe fire conditions can occur under a variety of fuel loadings and ranging from heavy to moderate-light. The most important variable affecting the degree of artifact thermal damage observed during the fire simulations was wind velocity, which affected the flame angle and the amount of potential heat energy emitted towards the experimental artifacts. Of course, during an actual wildland or prescribed fire there are a myriad of variables that can affect fire severity and fire impact on archaeological resources. However, the results of this research project should provide archaeologist with empirical data from which to adequate assess the potential impact of natural fire on archaeological resources given a particular set of variables.

Table 4.7: Wildland fire simulation summary data.

Trial	F.load (ton/a)	W.vel. (mph)	FlmL (m)	FlmH (m)	FlmA (deg°)	MxTU (°C)	MxTL (°C)	PkRT (sec)	FluxSR (kw/m^2)	Talt
1	8.67	5-6	0.77	0.54	45.5	814.0	480.2	13-42	27.9	H
2	8.67	5-6	0.76	0.47	54.7	888.0	595.1	25-82	20.3	H
3	8.67	5-6	0.76	0.43	55.4	835.0	445.4	20-74	16.8	H
4	6.33	5-6	1.2	0.73	52.1	649.7	382.1	15-22	18.6	H
5	6.33	5-6	1.2	0.66	54.5	689.6	286.5	12-37	33.1	H
6	6.33	5-6	1.1	0.71	49.2	702.0	201.4	13-27	18.9	H
7	4.34	5-6	none	none	none	664.9	208.9	9-20	14.4	H
8	4.34	5-6	0.76	0.38	58.3	819.0	617.6	7-26	19.9	H
9	4.34	5-6	0.76	0.46	52.9	592.3	343.0	8-32	22.0	H
10	4.34	2-3	1.2	0.85	43.5	598.5	340.8	2-20	28.9	M
11	4.34	2-3	1.2	0.85	44.5	571.5	243.9	7-14	30.7	M
12	4.34	2-3	1.1	0.76	46.6	676.8	314.6	2-19	34.5	M
13	8.67	2-3	1.2	0.85	43.5	608.8	310.1	20-40	32.0	M
14	8.67	2-3	1.2	0.84	44.5	582.5	230.7	10-19	31.7	M
15	8.67	2-3	1.1	0.76	46.6	509.2	229.5	14-28	24.2	M
16	6.33	2-3	1.1	0.82	38.8	524.6	220.8	5-29	26.6	M
17	6.33	2-3	1.1	0.83	41.6	526.8	309.9	9-30	21.3	M
18	6.33	2-3	1.2	0.87	41.0	708.0	398.6	4-25	26.2	M
19	8.67*	2-3	1.3	0.90	46.5	630.5	446.2	6-34	2.7	M
20	8.67*	2-3	1.4	0.85	45.8	603.8	409.9	11-48	10.6	M
21	8.67*	2-3	1.2	0.87	43.4	528.0	323.8	6-22	3.1	M
22	4.34*	2-3	1.3	0.86	46.5	581.0	322.1	3-22	8.3	L
23	4.34*	2-3	1.2	0.80	47.3	556.6	225.0	9-21	17.0	L
24	4.34*	2-3	1.4	1.0	42.0	617.7	313.9	8-28	9.3	L
25	1.00	2-3	0.64	0.46	43.2	319.6	163.0	4-8	6.0	VL
26	1.00	5-6	0.52	0.37	44.4	498.8	287.2	4-10	12.5	VL

Code Definitions:

F.load=Fuel Load ***W.vel***.=Wind Velocity ***FlmL***=Flame Length ***FlmH***=Flame Height ***FlmA***=Flame Angle ***MxTU***=Maximum Upper Surface Temperature (artifact) ***MxTL***=Maximum Lower Surface Temperature (artifact) ***PkResT***=Residence Time of Peak and near Peak Temperature (range) ***FluxST***=Peak Total Soil Flux (convective and radiant) measured at sediment surface ***FluxSR***=Peak Radiant Soil Flux measured at sediment surface ***FluxST***=Peak Total Air Flux (convective and radiant) measured 25cm above sediment surface ***Talt***=Thermal Alteration of Artifacts (H = high degree, M = moderate degree, L = low degree, VL = very low degree)

* Fuel placed on sediment bed and artifacts during fire simulation.

Figure 4.1: Flaming Combustion within chamber during experimental trial.

Figure 4.2: Interior of Combustion Chamber showing burn table.

Figure 4.3: Sediment bed with artifacts, thermocouples, and radiometers.

Figure 4.4: Experimental artifacts pre-burn.

Figure 4.5: Experimental artifacts post-burn (note thermally fractured biface, quartzite flake, glass, and delaminated shell).

Figure (4.58)

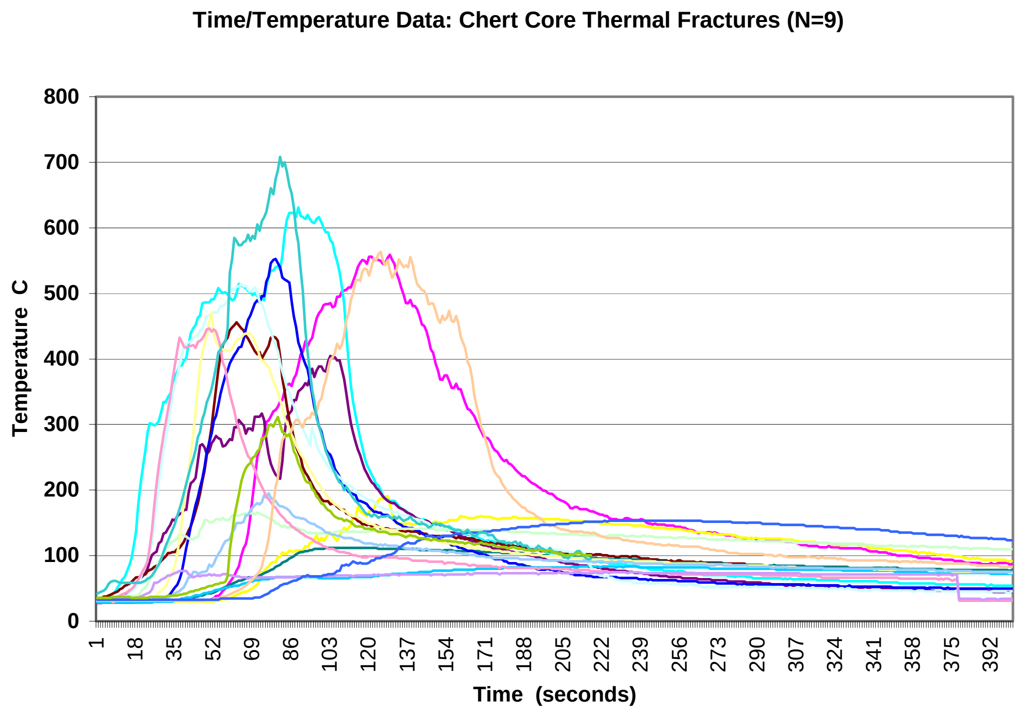


Figure (4.59)

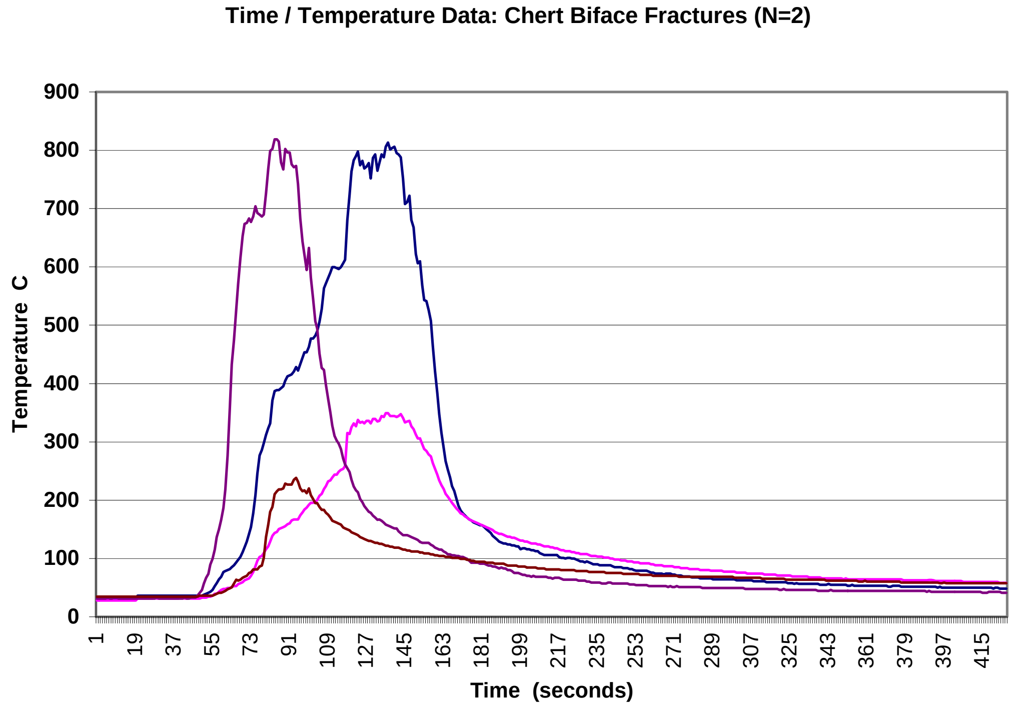


Figure (4.60)

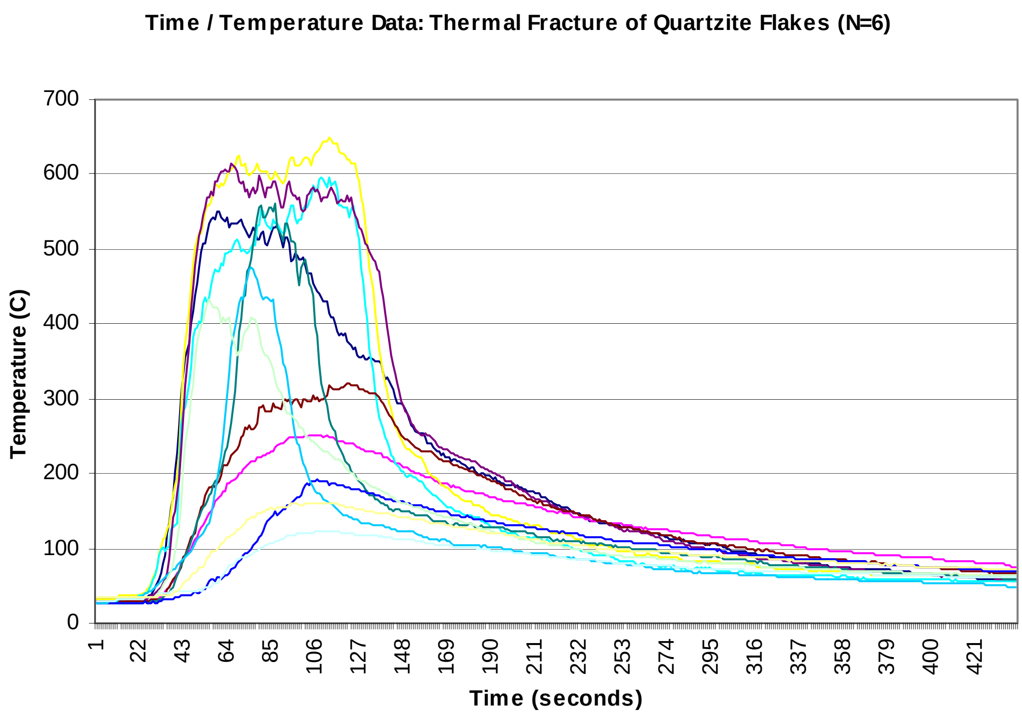


Figure (4.61)

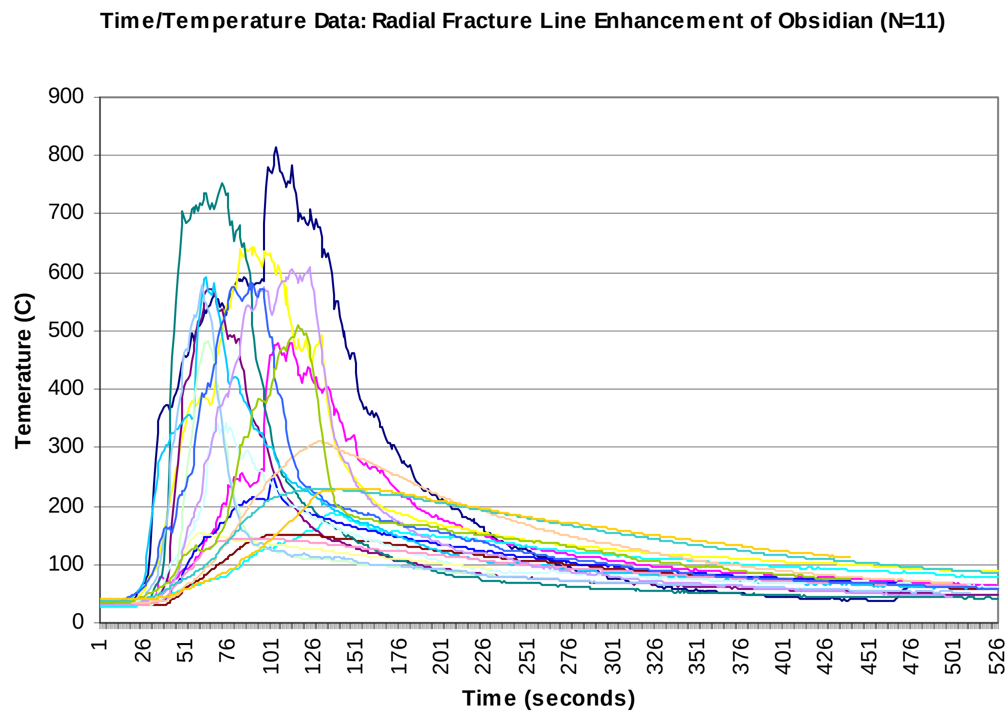


Figure (4.62)

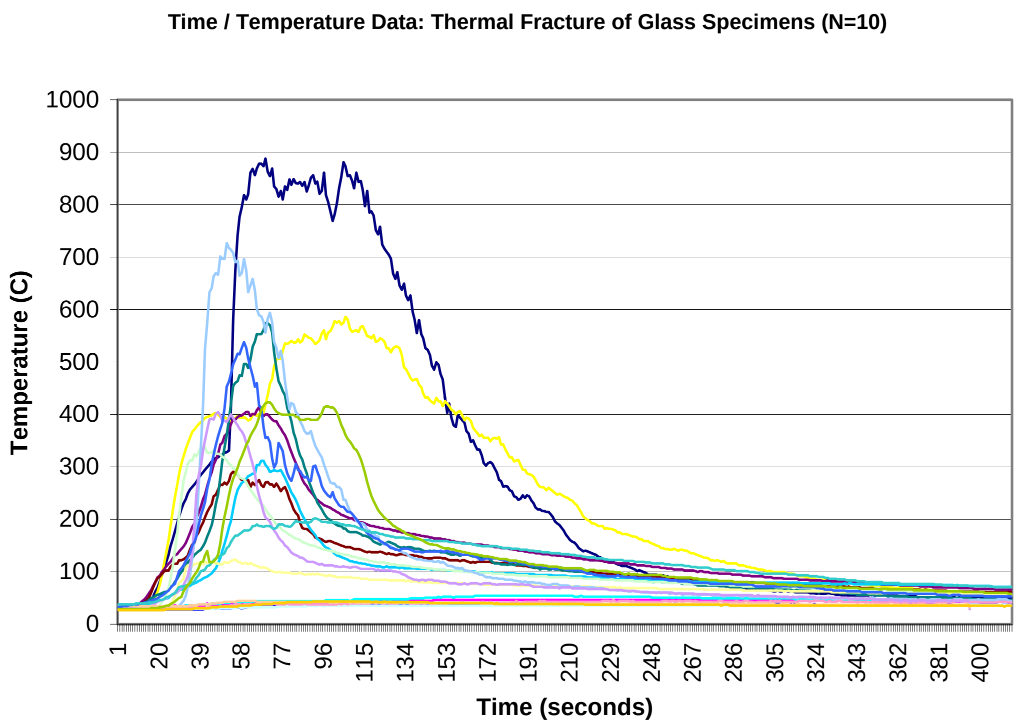


Figure (4.63)

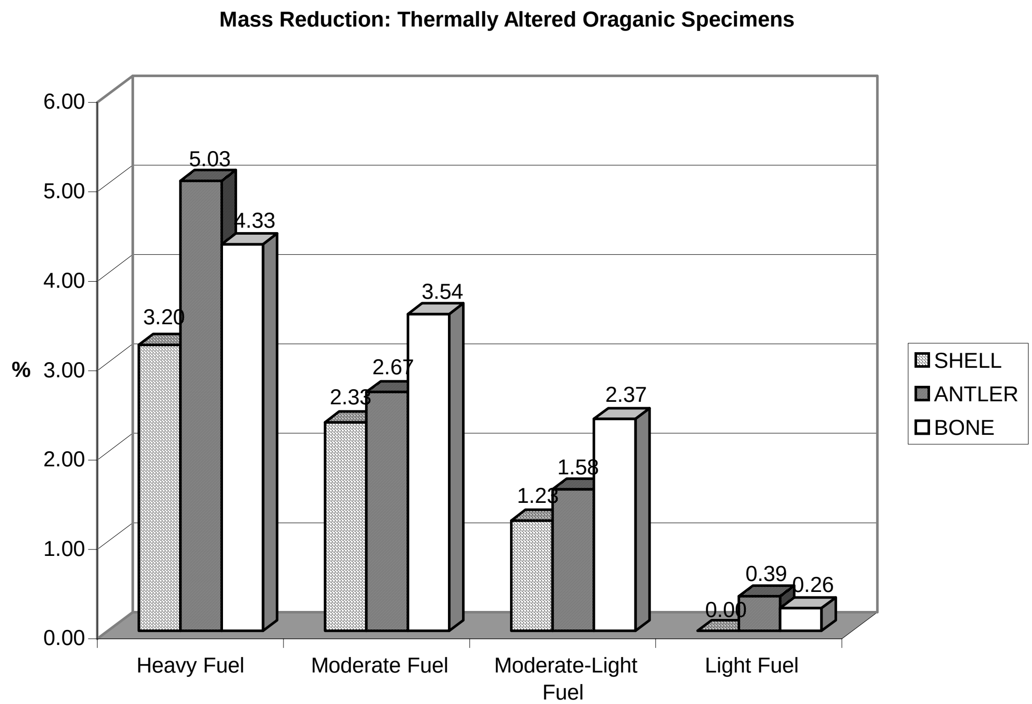


Figure (4.64)

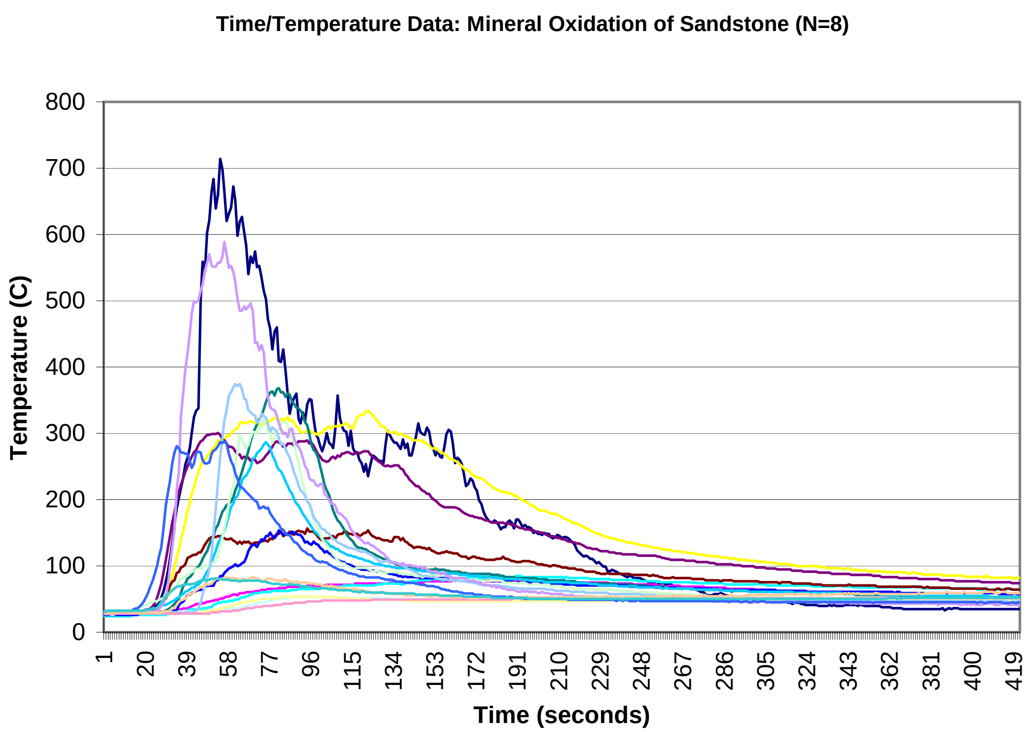


Figure 4.63: Mesa Verde sandstone thermally altered by wildland fire.

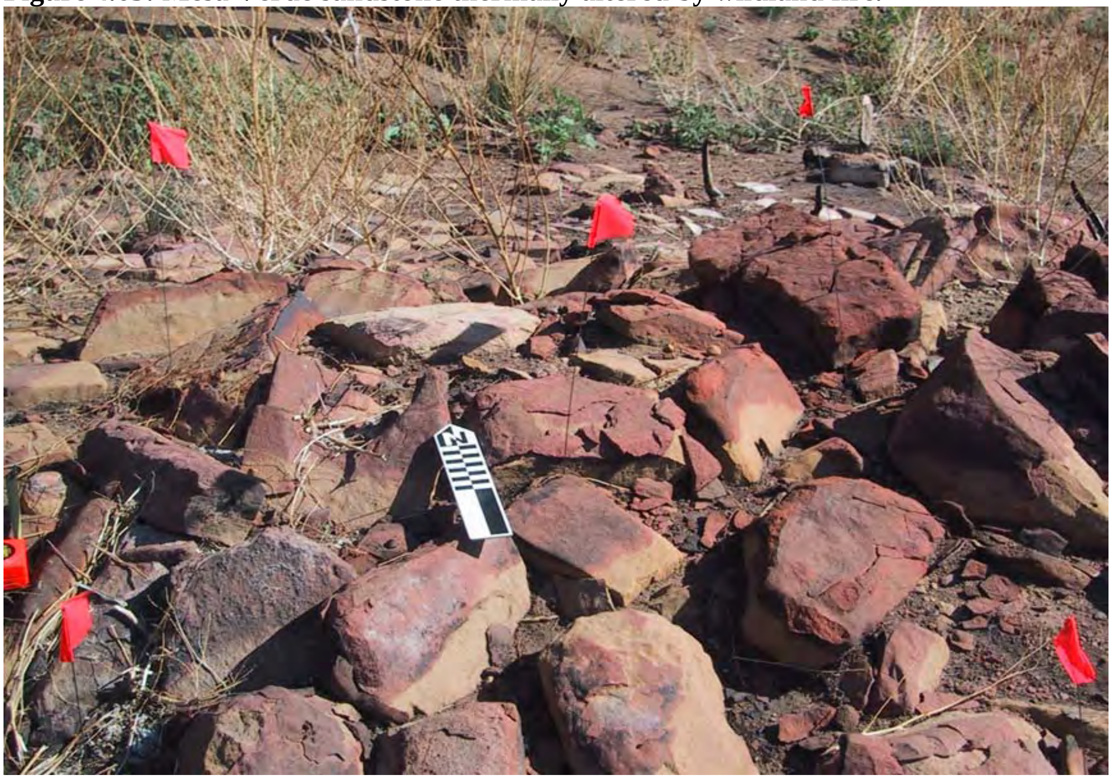


Figure 4.64: Experimental thermal alteration of Mesa Verde Sandstone (L-R, Light, Moderate, High).

CHAPTER 5
THE IMPACT OF WILDLAND FIRE ON ARCHAEOLOGICAL RESOURCES AT MESA VERDE NATIONAL PARK: A SAMPLING STRATEGY

Introduction

Several large wildland fires have occurred at Mesa Verde National Park in recent years, particularly in 1996 and 2000. Given the high density of Ancestral Pueblo sites located within the park and the frequent incidence of wildland fire in the area, Mesa Verde presented a unique opportunity to study the impact of wildland fire on archaeological resources. Previous fire related research conducted at the park has included post-fire archaeological survey, rehabilitation and stabilization work, as well as general fire impact assessments (Anderson 2000; Eininger 1990; Fiero 1995; Ives et al. 2002; Romme et al. 1993). Oppelt and Oliverius 1993 have performed experimental research focused on addressing the impact of fire retardant on pottery sherds. In addition, recent vegetative research at Mesa Verde by Floyd et al. 2000 has established a fire history for the park. However, no researchers have systematically addressed the impact of wildland fire on surface artifacts and architectural features at Mesa Verde National Park.

Accordingly, a fieldwork project focused on systematically recording the impact of several major wildland fires on Ancestral Pueblo sites at Mesa Verde National Park was conducted during the present dissertation project. In total, 72 Pueblo I –III open-air habitation sites (burned during the 2002 Long Mesa, 2000 Bircher, 2000 Pony, 1996 Chapin 5, 1989 Long Mesa, and the 1934 Wickiup Point fires) were incorporated into the fire effects sampling project. Portions of architectural features and surface artifact middens were sampled using pre-defined thermal alteration codes and sample units. The purpose of the research was to assess the impact of wildland fire on archaeological resources at the park by developing a systematic sampling strategy to be implemented at selected archaeological sites.

In order to achieve this goal fire effects sampling was conducted by collecting data through small spatially defined units rather than at an all-encompassing large-scale site-by-site basis.

Ultimately, the research at Mesa Verde National Park was focused on addressing the following questions related to the impact of wildland fire on archaeological resources at the park.

1. How have sites, features, and artifacts been impacted by wildland fire, and is the impact significant? Have archaeological materials been damaged, and what are the long-term implications concerning the preservation of those resources?
2. What types of archaeological materials are most at risk, and which are most resistant to thermal alteration?
3. What do the effects of wildland fire on archaeological resources look like 1-2yrs, 5-10yrs, 15-20yrs, 20-40yrs after a fire? Are the effects of a specific fire discernable over a period of several years?
4. What is the variability associated with fire effects between archaeological sites, and between artifact classes? How does site type, artifact class, fire intensity/fuel load affect this variability?
5. As a site formation process, how significant is the impact of fire on the way in which archaeologist interpret the record? Does the thermal alteration of artifacts affect their diagnostic or interpretive potential? Can a naturally occurring site formation process such as fire mimic patterns seen in the archaeological record that are normally attributed to human behavior (e.g. hearths, heat-treated lithics, etc.)?

The results generated by the project will provide useful assessments regarding the vulnerability and resilience of various artifacts classes and architectural features to wildland fire.

Research Design

In order to assess the immediate and long-term impacts of the 2002 Long Mesa, 2000 Bircher, 2000 Pony, 1996 Chapin 5, 1989 Long Mesa and 1934 Wickiup Point fires on archeological resources at Mesa Verde National Park, a systematic sampling strategy was designed. The sampling strategy was developed and modified from the methods used by Lentz et al. (1996) in their study of the impact of the Henry Fire on archaeological resources in the Jemez Mountains of New Mexico. Sampling methods were non-invasive and involved in field coding of various attributes associated with the thermal alteration of surface artifacts and architectural features. No sub-surface sampling, excavation, or specimen collection was performed. All data was collected using concise field forms developed specifically for the project (Appendix 4, data forms, data CD). Data collection at the selected sites was implemented using a three-part system of data forms. First, environmental data regarding each site's topographic location, slope and aspect, GPS coordinates, and burned vegetation composition were recorded. Information regarding the degree of combustion of burned fuels was obtained using a modified version of the post-fire assessment form used by Yosemite National Park. Information regarding the extent of combustion of small fuels (<1") and large fuels (1-3" and >3") was categorized from scorched to heavily burned based on pre-defined criteria. In addition, observations regarding the estimated percentage of combustion affecting each burned strata (subsurface, mineral soil, surface, understory, crown) on site was also recorded. This information combined with information concerning the degree of combustion observed on small and large fuels were used to establish an overall burn intensity assessment for the site in general. The overall site burn intensity assessment was categorized into one of three ordinal level classifications: *Low* (duff burned, no ladder fuels burned, no canopy burned); *Moderate* (duff consumed, ladder fuels burned, isolated crown burn or torching); or *Severe* (duff, ladder, and crown consumed).

Following the documentation of environmental and burn intensity data, the second portion of the data collection process was initiated. This was developed to assess the impact wildland fire on sandstone architectural materials at each of the selected sites. Prior to sampling a sketch map of the site was drawn on the reverse side of the architectural data form denoting a basic overview of the site as well as the position of the sample unit relative to the site datum. In addition, an overview sketch of the sample unit illustrating each specimen included in the sample was also documented on the data form. Architectural fire effects sampling was conducted using a 1x1m sample unit that was positioned over an accumulation of architectural surface rubble that was associated with an architectural feature, generally a roomblock or kiva. Each masonry element or fragment contained within the sample unit was numbered and coded for thermal alteration attributes and descriptive information such as maximum dimensions (length, width, thickness), weathering (1 light, 2 moderate, 3 heavy), material type, and specimen description was also recorded. The definitions for each of the thermal alteration codes used in the study are provided in Table 5.1.

Table 5.1: Definitions of thermal alteration codes use in study.

CB = *Combustive Residue* – The presence of tar deposits on the surface of a specimen formed as a by-product of the pyrolysis and combustion of organic materials. The residue is a by-product of combustion and is not composed of pure carbon, nor is it an intact organic compound (DeBano 1998). It is a highly nitrogenous condensate tar substance (Yokelson et al. 1997). The residue can be tacky or semi-solid immediately post-fire and generally appears as dark brown to black droplets on the surface of a specimen, may give artifacts a blackened appearance if sufficiently combusted.
CC/OX = *Color Change/Oxidation* – (1). An overall darkening or reddening of a specimen from its original color. It is generally the result of exposure to temperatures sufficient enough to alter the mineral composition of the specimen (this definition used to code sandstone blocks within architectural sample units) (i.e., Cliff House Formation Sandstone changing from its original orange-buff to a deep red color).
(2). The presence of and orange/brown discoloration on an artifact. It is generally due to the presence of oxidized sediment on a specimen where sediment had adhered to its surface prior to exposure to heating. Heating of the sediment results in discoloration that adheres or permeates the surface of a specimen.
POX = *Paint Oxidation*– The oxidation of pigment (organic or mineral) on decorated ceramic specimens. Alterations can include a change in color from the original pigment (black to red), or the combustion of the pigment entirely.
CC = *Color Change* – (lithic specimens only) An observable color change of a specimen from original, pre-fire, color. Generally due to an alteration in the mineral composition of a specimen during exposure to heat.
CZ = *Crazing* – The presence of fine, non-linear or latticed cracks on the surface of a specimen.
SP = *Spalling* – The exfoliation of a portion of the original surface of a specimen due to differential heating and pressure release. It is generally the result of steam buildup in areas of the specimen that have impurities or moisture content.
SPS = *Spall Scars* – The presence of concave depressions on the surface of a specimen where it is evident that a portion of the surface was exfoliated due to spalling, but the actual spall was not observed in situ. Over time, associated spalls have weathered or eroded.

PL = *Potlid Fracturing (lithic specimens only)* – Similar to spalling, but specific to lithic artifacts manufactured from chert. The fracture is characterized by a circular pit on the surface of the specimen. The pit represents the area in which the original portion of the surface has been exfoliated due to differential heating and pressure release. The exfoliated section is generally circular, flat on the dorsal side, and convex on the ventral side (resembling the lid of a cooking pot).
FR = *Fracturing* – The fracturing of a specimen into multiple pieces, and/or the presence of fractures or fissures that penetrate deeply into a specimen.
WFR = *Weathered Fracturing* – The fracturing of a thermally altered architectural block over time due to mechanical weathering. Fine cracks or fracture lines induced by exposure to heat become exacerbated due to mechanical weathering processes. Fracturing is often patterned and affects a large portion of the specimen.

Figures 5.1 through 5.6 illustrate examples of the most common form of thermal alteration observed during the study (sandstone oxidation/spalling, weathered fracturing of sandstone, oxidative staining and combustive residue on sherds, thermal spalling of sherds, lithic thermal fracture, chert thermal fracture and potlid fracture) (Figures provided at the end of the chapter).

If a specimen exhibited thermal alteration, the type(s) thermal alteration, and total portion of the specimen (% estimation of total surface area of specimen) affected was recorded. The most common forms of thermal alteration affecting sandstone architectural materials included oxidation, thermal spalling, thermal fracturing, and weathered fracturing. If a specimen exhibited thermal spalling, the in situ spalls were counted and weighed (g) as a combined total. This combined weight of the spalls was then divided by the total weight of the specimen from which the spalls were exfoliated to derive a percent mass loss estimate. The percent mass loss estimate was used as an estimate to roughly quantify the amount pre-fire mass lost due to thermal spalling for each affected specimen. The same process was also performed for specimens that exhibited thermal fracturing and heat-induced weathered fracturing.

The third phase of the data collection process involved thermal alteration attribute coding of surface artifacts, generally located within midden areas at the selected sites. Initially, sampling was accomplished using 1x1m sample unit; however, after sampling at a few sites with light midden scatters it became apparent that a 10x1 transect was a more appropriate spatial unit from which to adequately sample surface artifacts. Codes were used to record typological and functional attributes of sampled artifacts. Additional descriptive information regarding estimated specimen weathering (1 light, 2 moderate, 3 heavy), and maximum dimensions (length, width, thickness) was also recorded. In addition, each artifact was analyzed for discernable evidence of thermal alteration. Affected specimens were coded for observed type(s) of thermal alteration and for the extent of thermal alteration (estimated portion of artifact surface area affected by thermal alteration) present. Thermal spalling and fracturing of specimens was only recorded when the exfoliated or fractured portions of a specimen were observed in situ. Descriptive artifact data, thermal alteration data for each artifact, and environmental site data are summarized in tabular form in Appendix 4, Table 5.2 a, b, c, d, on the data CD provided with the dissertation.

Selected Mesa Verde Sites

In total, 72 Pueblo I-III open-air habitation sites were sampled for fire effects across 6 different fire areas burned during wildland fires between 1934 and 2002. In order to sample the potential variability in fire effects at the selected sites, sampling was conducted at sites located within heavy piñon-juniper fuels along canyon slopes and mesa tops, and at sites located within lighter mixed grass and mountain shrubland fuels along canyon bottoms and large open benches. In addition, to address the long-term consequences of thermal alteration and resilience of specific forms of thermal alteration sites were selected from areas that were burned at time intervals ranging from 2 months to 68 years. Wildland fire names/dates, general site locations, and associated site numbers of the sites that were included in the project are listed below.

2002 Long Mesa Fire Sites: (Chapin Mesa, W. Chapin Mesa, Park Mesa) 5MV388, 5MV763, 5MV769, 5MV782, 5MV3477, 5MV3557 (n=6).

2000 Bircher Fire Sites:

(Morefield Canyon) 5MV1082; 5MV1083, 5MV1921, 5MV1922, 5MV1927, 5MV1928, 5MV2843, 5MV2877, 5MV2885, 5MV2893, 5MV2899, 5MV2963 (n=12).

(Whites Canyon) 5MV954, 5MV956, 5MV957, 5MV958, 5MV960, 5MV963, 5MV963, 5MV 965, 5MV966, 5MV2534 (n=10).

(Prater Canyon) 5MV3066, 5MV3146, 5MV3163, 5MV3173, 5MV3179, 5MV3180, 5MV3194, 5MV4512 (n=8).

(Moccasin Mesa) 5MV3256, 5MV3266, 5MV3271, 5MV3287, 5MV3289 (n=5).

Whites Mesa) 5MV4627 (n=1). (Waters Canyon) 5MV2669) (n=1).

2000 Pony Fire Sites: (Wetherill Mesa) 5MV1624, 5MV1626, 5MV1631, 5MV1633, 5MV1651, 5MV1652 (n=6).

1996 Chapin #5 Fire Sites: (Battleship Rock Community) 5MV2475, 5MV2476, 5MV2477, 5MV2479, 5MV4021 (n=5). (Battleship Rock East) 5MV3689, 5MV3707, 5MV3733, 5MV3745, 5MV3749 (n=5)

1989 Long Mesa Fire Sites: (Long Canyon) 5MV1153, 5MV1154, 5MV1157, 5MV1160, 5MV1164, 5MV1168, 5MV1172, 5MV1176, 5MV3915 (n=9).

1934 Wickiup Point Fire Sites: (Finger Ridge above E. Wickiup Canyon) 5MV1947, 5MV1949, 5MV1950, 5MV1978 (n=4).

Brief site narratives including general site information and summaries of the fire effects data collected at each site are provided in Appendix 4, Site Narratives, data CD. In addition, descriptive artifact data and thermal alteration attribute codes recorded form each site are provided in Appendix 4, Table 4.2, data CD. Brief fire effects summary data for sites grouped by geographic location and fire name/date are provided below.

WHITES CANYON SITES (2000 Bircher Fire)

Whites Canyon was burned during the 2000 Bircher Fire that impacted approximately 23,000 acres (9311 ha), 19,607 acres (7938 ha) of which were located within Mesa Verde National Park. Fire effects sampling at archaeological sites was conducted in the middle portion of Whites Canyon along the western side of the drainage. Architectural and surface artifact thermal alteration sampling was carried out at ten Pueblo II-III habitation sites located along the lower portions of the canyon near the transition between the terminal talus slope and the canyon bottom. Pre-fire fuels in the vicinity of the sites consisted of mixed grass and brush species with an admixture of dispersed piñon-juniper encroaching downward from the canyon slope. In general, the predominantly light fuels resulted in light to moderate fire intensities in the sample area, and subsequently, low to moderate degrees of thermal alteration were recorded at the selected sites. However, burning in the sample area was not consistent resulting in a mosaic pattern of burned and unburned areas that were recorded near one of the sampled sites. In addition, heavy burning was observed at an additional site due to the presence of heavily charred piñon-juniper fuels on site. These were, however, exceptions to the general trend of light to moderate burn intensities that were generally observed within the sample area.

In general, the mixed grass and brush fuels in the lower portions of Whites Canyon produced low to moderate amounts of heat energy. This resulted in thermal alteration of architectural materials characterized by light oxidation and thermal spalling. Surface artifacts were often recorded as showing no discernable evidence of thermal alteration, and the limited thermal alteration that was observed generally took the form of combustive blackening and oxidative staining. Site #957 was an exception exhibiting the greatest degree of thermal alteration for the overall sample, largely due to the presence of heavy fuels on-site. Site #966 was located at a transition between burned and unburned fuels and generally sustained very minor burning and thermal alteration. The results of fire impact sampling in Whites Canyon illustrate the important relationships between fuel load, fire intensity, the production of heat energy, as it relates to the subsequent impact of burning of surface archaeological materials. The results also show that wildland fire may often produce a mosaic of burn intensities, even within a limited area. The combined thermal alteration data collected for architectural and surface artifact sample units are provided below.

The combined architectural sample was comprised of 101 Cliff House Formation sandstone blocks. Oxidation was observed for 91.09% of the sample, and thermal spalling was observed at relatively low frequency of 19.80%. Thermal spalling resulted in an estimated 3.61% loss in the pre-fire mass of affected specimens. Only one specimen exhibited thermal fracturing resulting in an observed frequency of less than 1%, but yielding a percent mass loss estimated of 32.60% (specimen fracturing in to halves). The combined percent mass loss estimate for thermally spalled and fractured specimens was calculated at 5.17%. In addition, combustive blackening was observed for 5.94% of the sample, and nine specimens (8.91%) did not exhibit any discernable evidence of thermal alteration. On average, an estimated 24% of the surface area of sampled blocks was affected by thermal alteration, predominantly oxidation. The moderate levels of oxidation and limited degree of thermal spalling observed for the overall sample are consistent with the environmental data collected at each site that generally supported the consensus that light to moderate fuels and burn severity characterized the Bircher fire conditions in the Whites Canyon study area.

In total, 215 surface artifacts representing 63.72% pottery sherds and 35.81% lithic materials, predominantly mudstone and quartzite primary and secondary flaking debris, were analyzed for evidence of thermal alteration. The extent of thermal alteration of surface artifacts across the ten sites was limited, with 71.63% of the combined sample exhibiting no observable evidence of thermal alteration. Combustive blackening and oxidative staining were observed on an equal number of specimens (37) for an overall frequency of 17.21% for each. Two black-on-white sherds exhibited paint oxidation for an overall frequency of less than 1%, affecting only 4.16% for the total number of black-on-white sherds represented in the sample. Thermal spalling was observed on three specimens, one large trough metate (igneous), one mudstone core, and one corrugated sherd for an overall frequency of 1.40%. In addition, thermal fracturing was also observed on three specimens; the above mudstone core, one chert unspecified fragment, and an additional corrugated sherd, affecting only 1.40% of the combined artifact sample. The results of thermal alteration attribute coding for surface artifacts are consistent with those observed for the architectural sample. Oxidative staining and combustive blackening were observed at moderate levels, and catastrophic forms of thermal alteration were very limited. In general then, the light to moderate fire intensities had an accordingly light to moderate negative effect on surface archaeological materials sampled at the ten Whites Canyon Pueblo II-III sites

MOREFIELD CANYON SITES (2000 Bircher Fire)

Morefield Canyon was burned during the extensive 2000 Bircher Fire, which burned approximately 19,607 acres (7938 ha) within Mesa Verde National Park, and over 23,000 acres (9311 ha) in total. The burn severity and impact of the fire within Morefield Canyon was largely influenced by fuel load composition, topography and man-made fuel breaks. Twelve Pueblo II-III habitation sites located within Morefield Canyon were incorporated into the fire effects study. Four sites, #1082, 1083, 1921, 1922, were situated in upper Morefield Canyon along the canyon bottom, near the Morefield Campground. Fuels in the vicinity of these sites were characterized by a mix of grasses, brush (sage, mountain mahogany, oak) and dispersed piñon-juniper. The burn severity and subsequent impact of the fire on archaeological resources at these sites was recorded as moderate. An additional seven Pueblo II-III Morefield Village sites were sampled on the western slope of Morefield Canyon. The impact of the fire at these sites was generally severe due to the predominantly heavy piñon-juniper fuels and severe wildland fire conditions that occurred in the area. The twelfth site, #2963, was situated within mixed fuels along the canyon bottom down slope from the Morefield Village sites. The results of fire effects sampling at the selected sites illustrated the fundamental relationships between fuel load/composition, landscape geology, and wildland fire behavior as they condition the degree of thermal alteration affecting surface archaeological materials.

Twelve Pueblo II-III habitation sites located within the margins of Morefield Canyon were sampled to assess the impact of the 2000 Bircher Fire on archaeological resources located in this portion of the park. The effect of the fire on the selected sites was largely conditioned by fuel composition, and to a lesser extent topographic location associated with each of the sites. Seven sites were located on the western margin of the canyon slope along benches and finger ridges obtruding from the talus. These localities were situated within heavily charred and combusted piñon-juniper stands. An additional five sites were located in the canyon bottom within smaller fuels comprised of a mix of grasses, brush, and widely dispersed piñon-juniper. These sites experience moderate fire severity and generally sustained moderate levels of thermal alteration to surface architectural rubble and midden artifacts. Fire effects sampling within Morefield Canyon illustrated the important relationship between fuel load, fire severity, and thermal alteration of surfaces archaeological resources. A summary of the fire effects data collected for the overall sample of Morefield canyon sites, and for sites grouped by topographic location and fuel type (canyon slope/piñon-juniper and canyon bottom mixed fuel) is provided below.

In total, 114 individual masonry elements were coded for thermal alteration attributes. Oxidation was observed for 95.61% of the sample, and thermal spalling was recorded for 49.12% of sampled specimens. Thermal fracturing was observed for only 4.39% of the overall sample, although it contributed to a significant loss in the estimated pre-fire mass of affected specimens, calculated at 26.05%. Thermal spalling attributed to an estimated 5.86% loss in the pre-fire mass of affected specimens, and the percent mass loss estimate for thermally spalled and fractured combined was estimated at 6.96%. Combustive blackening was recorded for 15.79% of the sample, and overall only 4.39% of the sample did not show any discernable evidence of thermal alteration indicating that the 2000 Bircher Fire affected the majority of architectural rubble sampled at the selected sites.

Among the seven sites sampled from canyon slope and piñon-juniper contexts, a total of 72 masonry elements were analyzed for evidence of thermal alteration. Oxidation was recorded at an observed frequency of 98.61%, thermal spalling at 70.83%, thermal fracturing 6.94%, and combustive blackening 19.44%. Thermal spalling attributed to an estimated loss in the pre-fire mass of affected specimens of 6.75%, and thermal fracturing contributed to an estimated mass loss of 26.05%. Thermal spalling and fracturing combined, yielded a percent mass loss estimate of 8.24%. Only 1.39% of specimens sampled did not show any discernable evidence of thermal alteration. The high prevalence of oxidation and thermal spalling within the canyon slope/piñon-juniper fuel sample is indicative of high fire severity. In general, architectural rubble located at sites located on the canyon slope within heavy piñon-juniper fuels sustained a significant negative impact as a result of being burned during the 2000 Bircher Fire.

In contrast, the sample of sites grouped into the canyon bottom/mixed fuel category sustained light to moderate fire effects likely due to reduced fuel load and lesser fire severity. A total of 42 individual masonry elements were coded for thermal alteration attributes among the five sites comprising the canyon bottom/mixed fuel sample. Oxidation was observed for 90.48% of the sample; however, thermal spalling was observed at a much lower frequency at only 11.90%, and thermal fracturing was not recorded within the sample. Combustive blackening was also observed for only 11.90% of the sample. More importantly, nearly 10% (9.52%) of specimens sample at sites from canyon bottom/mixed fuel contexts did not show any observable evidence of thermal alteration. The low incidence of thermal spalling combined with the notable lack of thermal alteration within the sample are indicative of moderate fire severity. The relationship between fuel load, fire intensity, and degree of thermal alteration observed on sandstone architectural rubble is well illustrated by the differences in the observed frequency of catastrophic forms of thermal alteration such as thermal spalling and fracturing at sites located on canyon slopes within heavy piñon-juniper fuels as compared to those located on the canyon floor within lighter mixed fuels.

The combined sample of surface artifacts included a total of 284 artifacts comprised of 68.66% pottery sherds and 31.34% lithic materials (primary and secondary flaking debris). Combustive blackening and oxidative staining were the most common forms of thermal alteration recorded for the combined sample at 38.38% and 26.41% respectively. Catastrophic forms of thermal alteration such as thermal spalling and fracturing were also observed at notable frequencies of 7.39% and 10.21% each. In addition, potlid fracturing, crazing, and heat-induce color alterations affected 15-19% of chert specimens within the overall sample. Paint oxidation was observed on 12.32% of the black-on-white pottery sherds recorded in the artifact sample. However, 35.21% of artifacts sampled did not exhibit any discernable evidence of thermal alteration. This is to be expected since the overall sample is comprised of sites that experienced severe fire intensity as well as sites that were exposed to moderate burn severity.

When the overall sample is divided into the canyon slope/piñon-juniper and canyon bottom/mixed fuel categories differences in the observed frequency of thermal alteration among surface artifacts begins to emerge. Within the canyon bottom/mixed fuel sample, 50.00% of surface artifacts sampled did not exhibit any observable evidence of thermal alteration. Moreover, catastrophic forms of thermal alteration such as thermal spalling and fracturing were observed at low frequencies, 4.17% and 2.50% respectively. Paint oxidation of black-on-white sherds was not observed among the 27 black-on-white sherds sampled. However, potlid fracturing, heat-induced color alteration, and crazing affected between 10-50% of the chert specimens sampled at the canyon bottom/mixed fuel sites suggesting that chert is particularly sensitive to thermal alteration. In addition, oxidative staining was observed on 15.83% of sampled artifacts, and combustive blackening was evident on 38.33% of artifacts also suggesting that these forms of thermal alteration occur under low to moderate wildland fire conditions.

In contrast, a significantly lower proportion of surface artifacts sampled at the canyon slope piñon-juniper sites were recorded as being unaffected by thermal alteration (24.39%). Moreover, catastrophic forms of thermal alteration such as thermal spalling and fracturing were observed at higher frequencies; 9.76% and 15.85%, compared to 4.17% and 2.50%

recorded for the canyon bottom/mixed fuel sites. In addition, paint oxidation affected 18.00% of black-on-white sherds sampled. However the incidence of crazing and potlid fracturing were not observed at elevated frequencies, recorded for 13-18% of chert specimens sampled. Oxidative staining was observed at a higher frequency of 34.15%, and the incidence of combustive blackening was at proportionally the same frequency of 38.41%. In general, catastrophic forms of thermal alteration indicative of severe fire intensity were observed at significantly greater frequencies within the canyon slope/piñon-juniper sample. This is consistent with the data collected regarding the impact of the fire on sandstone architectural rubble, and is representative of the extent of thermal alteration expected among surface artifacts that were subjected to severe wildland fire conditions.

Overall, the results of fire effects sampling at selected Morefield Canyon sites show that the impact of the Bircher 2000 Fire on archaeological resources was variable, and largely dependent on fuel load composition and fire severity. Architectural rubble becomes oxidized at low, moderate, or severe fire conditions; however, thermal spalling and fracturing was limited to sites that experienced severe wildland fire conditions. Similarly, thermal fracturing and spalling of surface artifacts was observed at greater frequencies among the severely burned sites, although chert artifacts seem to be affected at both moderate and high fire intensities. In addition, combustive blackening of surface artifacts also occurred at similar frequencies among the canyon slope/piñon-juniper and canyon bottom/mixed fuel sites. Nonetheless, the forms of thermal alteration that have the most significant negative implication for the preservation of archaeological materials subjected to wildland fire seem to be exclusive to the severely burned canyon slope/piñon-juniper sites.

PRATER CANYON SITES (2000 Bircher Fire)

Fire impact sampling was conducted on the western slope of Prater Canyon. This area was burned during the 2000 Bircher Fire. Pre-fire fuels on the canyon slope were dominated by piñon-juniper, with mixed brush and more sparsely distributed piñon-juniper encompassing the lower portions of the canyon slope as it trends towards the canyon bottom. The environmental data collected during sampling was indicative of severe fire intensity in which the once dense piñon-juniper over-story exhibited extensive charring and combustion, and the smaller dispersed fuels were observed to be nearly totally combusted.

Eight Pueblo II habitation sites located on middle to high canyon slope benches, and the terminal portion of the talus slope were sampled during the study. The overall impact of the fire on the selected archaeological sites was significant; however, the extent of thermal alteration was somewhat variable based on the location of the site on the canyon slope. Sites on the lower margins of the canyon were situated within a more dispersed mixed piñon-juniper and brush vegetative community, and subsequently exhibited a slightly diminished degree of thermal damage compared to sites situated within dense piñon-juniper fuels on the mid to upper portions of the canyon slope.

Two of the sampled sites were located on the lower portion of the canyon slope where fuels consisted of a mix of dispersed piñon-juniper and brush species. These sites sustained a moderate degree of fire damage compared the remainder of the sample, which was located on the mid to upper portions of the canyon slope within heavily burned piñon-juniper fuels. The impact of the fire on the sites located on the canyon slope within piñon-juniper fuels was severe.

In total, sixty-six individual sandstone architectural elements, the majority of which were derived from Cliff House Formation sandstone, were analyzed for evidence of thermal alteration. Oxidation was the most prevalent type of thermal alteration recorded for the combined sample, observed at a frequency of 98.48%. Thermal spalling within the overall architectural sample was also prevalent with an observed frequency of 63.64%. The percentage of mass loss resulting from thermal spalling was calculated at 4.91% for the combined sample of architectural rubble. Thermal fracturing occurred at a limited frequency of 3.03% for the overall sample, and interestingly fracturing was only observed at sites #3146 and #3163 that were, based on additional environmental and sample information, only moderately impacted by the fire. However, the greatest proportion of oxidation and thermal spalling was observed at sites located within heavy fuels on the upper portions of the canyon slope. Overall, only one specimen from the combined sample did not exhibit any discernable evidence of thermal alteration, and the impact of the fire on surface architectural materials generally ranged from moderate to severe.

The combined artifact sample included 177 artifacts comprised of 75.14% pottery sherds and 24.29% lithic materials, predominantly primary and secondary flaking debris. Combustive blackening accounted for the greatest proportion of thermal alteration that affected the overall sample, observed at a frequency of 46.33%. Oxidized soil staining was also fairly prevalent with 34.46% of the sample exhibiting this type of thermal alteration. Thermal fracturing was observed for only 4.52% of the sample and thermal spalling was observed at an even more limited frequency of 2.26%. In addition, two chert specimens (1.13%) exhibited heat-induced color alteration, potlid fracturing, and crazing. However, these forms of thermal alteration were only observed for approximately 8% of chert specimens sampled. Three (1.69%) black-on-white pottery sherds exhibited paint oxidation in which exposure to heat had oxidized the black pigment on the sherds. In total, 30.51% of the combined sample did not exhibit any observable evidence suggestive of thermal alteration. The results of artifacts sample are somewhat discordant with those recorded for the architectural sample in which observable forms of thermal alteration were more prevalent. However, this trend has been observed for several other subsets of sites sampled during the fire effects study. It is suggested that several variables such as surface area, ground surface profile, material composition, and weathering processes contribute to degree of thermal alteration that is observable on architectural rubble versus surface artifacts. Nonetheless, the combined artifact sample for the Prater Canyon sites did exhibit a moderate degree of thermal alteration, particularly in the form of combustive residue deposits and oxidative staining. This is within the range of thermal alteration expected given the degree of fire severity observed at the sampled sites.

MOCCASIN MESA SITES (2000 Bircher Fire)

Five Pueblo I-III habitation sites located on Moccasin Mesa were assessed for fire damage using the methods outlined for the study. The mesa was burned during the extensive 2000 Bircher fire. Pre-fire fuels in the vicinity of the sample area were dominated by mature piñon-juniper. Based on post-fire environmental data collected during the study, the overall burn intensity assessment for the sample area was recorded as severe. This was especially apparent due to the numerous large piñon-juniper snags that exhibited extensive combustion in which the original tree was reduced to burned out stumps or trunks. Consequently, the impact of the fire on the sampled archaeological sites was generally observed as severe as well, with architectural rubble sustaining the greatest degree of thermal alteration.

The architectural sample show included a total of thirty-six individual elements of architectural rubble derived from Cliff House Formation Sandstone. Oxidation affected the entire sample, observed at a frequency of 100.00%, and thermal spalling was prevalent as well occurring at an observed frequency of 80.56%. The average number of spalls observed for affected specimens was nine, and the percent mass loss estimate attributed to thermal spalling was calculated at 3.44%. Thermal fracturing of architectural rubble was observed at a frequency of 16.67%, resulting in an percent mass loss estimate of 23.34%. Thermal spalling and fracturing combined contributed to an estimated mass loss among affected specimens of 8.18%. Other forms of thermal alteration within combined sample were limited, with only one specimen exhibiting combustive blackening, and one was observed with spall scarring in the absence of in situ spalls (2.78% each). The portion of thermal alteration estimate for the overall architectural sample was estimated at 37%, indicating that on average, over one-third of the surface area of each specimen was visibly affected by thermal alteration. The high prevalence of oxidation and thermal spalling combined with the occurrence of limited thermal fracturing within the sample are indicative of severe fire intensity, and more importantly, have significant negative implications for the preservation of surface architectural materials on Moccasin Mesa.

In total, 127 surface artifacts comprised of 74.02% pottery sherds and 25.20% lithics were analyzed for evidence of thermal alteration. The majority of sherds, approximately 70%, were of the corrugated and black-on-white variety, and nearly the same proportion of lithics were comprised of primary and secondary flaking debris, predominantly representing chert raw material, but also mudstone and green quartzite. The most prevalent form of thermal alteration observed for the combined artifact sample was combustive blackening, observed at a frequency of 48.03%. Thermal fracturing was observed for 13.39% of the sample, and thermal spalling 8.66%, indicating that high levels of heat energy released from the fire has significantly impacted a reasonable percentage of the combined surface artifact sample. In addition, heat-induced color alterations and potlid fracturing was observed on approximately 28% of chert artifacts, further suggesting that surface artifacts experienced high levels of heat energy. Oxidative staining was recorded at a frequency of 12.60%, and other forms of thermal alteration of such as paint oxidation and crazing were negligible, recorded at frequencies of less than 1%. In addition, 37.80% of the combined sample did not exhibit any discernable evidence of thermal alteration. However, while combustive blackening and oxidative staining are relatively benign forms of thermal alteration, fracturing and spalling in which specimens are effectively destroyed are not. The information acquired through artifact sampling was consistent with that attained for architectural samples, which both are indicative of high fire severity and a significant negative impact on surface archaeological materials on Moccasin Mesa.

WATERS CANYON SITE (Bircher 2000 Fire)

Archaeological sampling in Waters Canyon was limited to one site largely due to the lack of suitable sites meeting the sampling criteria. The canyon was burned during the 2000 Bircher Fire, and burned fuels predominantly consisted of oak brush. Sampling at site #5MV2669 provided an opportunity to collect fire impact data on a canyon slope site located within an oak brush community. Data collection at the site offered limited insight into the impact of wildland fire on a canyon slope site situated within oak brush fuels.

The site is located on the eastern slope of Waters Canyon, approximately midway up the slope on a small bench. The site is surrounded by a dense stand of burned oak brush, although it is sparsely distributed in the immediate vicinity of the site. The burn intensity assessment for the site was recorded as moderate to severe; however, much of the site is devoid of dense oak brush growth. The site is a Pueblo II habitation comprised of dispersed architectural rubble associated with a probable roomblock feature, one kiva depression, a retaining wall, and a light scatter of surface artifacts.

Although a small portion of surface architectural rubble at the site was located within dense oak brush, and was subsequently heavily oxidized and spalled, the majority of the site's surface rubble was located in an open area experiencing moderate oxidation and limited spalling. Architectural sampling was conducted in an area representative of the site in general. The results of sampling show that 100.00% of the ten sampled blocks exhibited moderate oxidation at an average thermal alteration portion of 31%. No additional forms of thermal alteration were observed. The results are consistent with what would be expected for a site situated in an open area within an oak brush vegetative community.

The artifact sample included nineteen artifacts with 47.37% of the sample exhibiting combustive blackening and 21.05% exhibiting oxidation staining. No additional forms of thermal alteration within the sample were observed, and 36.84% of sample artifacts exhibited no discernable for of thermal alteration. These results are consistent with those recorded for the architectural sample and the burn intensity data collected for the site.

WHITES MESA SITE (2000 Bircher Fire)

Fire impact sampling from the 2000 Bircher Fire was limited to one archaeological site located on Whites Mesa. Unfortunately, few sites on the mesa met the sampling criteria outlined by the project's research design. The pre-burn vegetative community on the mesa was dominated by oak brush and mountain mahogany mixed with dispersed piñon-juniper. Sampling at the site offered a limited opportunity to collect fire impact data from a mesa top site located within oak brush fuels since all other mesa top sited sampled during the study were located within heavy piñon-juniper fuels.

Burned fuels in the immediate vicinity of the site are a mixture of grasses, dense brush, and dispersed piñon. The burn intensity assessment for the site was recorded as moderate to severe based on the heterogeneous fuel composition and differential burning intensities observed at the site. Surface architectural rubble at the site exhibited a significant degree of oxidation and thermal spalling, especially in areas where burned brush and yucca stumps were observed. A total of eight masonry blocks were sampled, generating an oxidation frequency of 100.00%, a thermal spalling frequency of 75.00%, and a thermal fracturing frequency of 12.50%. The greatest degree of spalling was observed on blocks closest to stumps of burned brush. Thermal spalling was attributed to an estimated 3.36% loss in the pre-fire mass of affected specimens. One thermally fractured specimen yielded a percent mass loss estimate of 27.66%. The average percent mass loss estimate for the combination of thermally spalled and fractured specimens was calculated at 7.87%, and the average portion of thermal alteration estimate for the entire sample was 36%.

Artifact sampling was conducted on the western margin of the site in a very light surface artifact scatter. Unlike the architectural sample unit, there was no evidence of heavy fuel combustion within the artifact sample area, and burned fuels were observed to be light and sparsely distributed. Only fifteen artifacts were sampled due to the nominal surface artifact distribution contained within the site area. The preponderance of sampled artifacts, 60.00%, exhibited no observable forms of thermal alteration. The most common form of thermal alteration observed was combustive blackening at a frequency of 40.00%. Only one artifact was observed with oxidative staining, and no additional types of thermal alteration were observed across the sample. The disparity in the degree of observed thermal alteration between the architectural sample and artifact sample is largely the result of the light fuels and a sparse artifact distribution associated with the artifacts sample. Overall, the site experienced thermal damage of variable magnitude in which architectural rubble near brush and yucca stumps exhibited significant degrees of oxidation and thermal spalling; whereas on the margins of the site surface artifacts exhibited only moderate amounts thermal alteration, mostly in the form of combustive residue deposits.

WETHERILL MESA SITES (2000 Pony Fire)

The 2000 Pony Fire burned approximately 1352 acres (547 ha) within the western-most portion of Mesa Verde National Park, and a total of approximately 5420 combined acres (2194 ha) on lands within the park and outside its boundaries. Within the park, the fire affected a significant portion of Wetherill Mesa where pre-fire fuels consisted predominantly of dense stands of mature piñon-juniper. Fire impact sampling was conducted at six Pueblo I sites located on Wetherill Mesa. In general, the selected sites experienced severe wildland fire conditions, and surface archaeological materials were significantly impacted; however, the density of architectural rubble and surface artifacts at most sites was limited.

Environmental data collected at each of the sites revealed that the piñon-juniper fuels were heavily combusted, often reduced to burned out stumps and trunks, indicating that the area experienced severe burning. Although the architectural rubble associated with the sampled Pueblo I sites had considerably smaller surface area compared to the larger more concentrated Pueblo II-III architectural rubble sampled elsewhere, significant levels oxidation and thermal spalling were observed at the Wetherill Mesa sites. In general, surface artifacts at the selected Pueblo I were spatially dispersed and observed in limited densities as well. The extent to which these conditions affected the validity of fire effects sampling is uncertain; however, the degree of thermal alteration of architectural sandstone and surface artifacts observed at each site was consistent and reasonably representative of the substantial fuel combustion observed in the area.

The combined sample of architectural rubble consisted of a total of 44 individual fragments of sandstone rubble. Oxidation affected 100.00% of the overall sample, and thermal spalling was observed for 79.55% of sampled specimens. Thermal spalling accounted for an estimated 4.59% overall loss in original mass of affected sandstone rubble. Thermal fracturing was observed at a limited frequency (2 specimens, 4.55%), but contributed to an estimated mass loss of 19.64%. Combined thermal spalling and fracturing resulted in a loss in pre-fire mass of 6.79% for the entire sample of architectural rubble. Additional forms of thermal alteration were not observed. On average, thermal spalling and fracturing affected an estimated 39% of the surface area of each sampled specimen. These results are representative of severe wildland fire conditions.

In total, 137 surface artifacts, comprised of 82.48% pottery sherds and 17.52% lithic materials, were sampled for thermal alteration attributes across the combined sample from six sites. Combustive blackening was the most prevalent form of thermal alteration observed, affecting 59.85% of sampled specimens. Oxidative staining was observed in limited quantities, affecting only 8.76% of the overall sample. Thermal fracturing and spalling of pottery sherds, quartzite primary flakes, one mano fragment, and one chert primary flake represented overall frequencies of 5.11% and 7.30% respectively. In addition, potlid fracturing affected 23.07% of the 13 total chert specimens recorded from the sample. Crazing was observed on only one chert specimen, at a frequency of 7.69% for the sample of chert specimens. In addition, heat-induced color change was observed on 61.54% of chert specimens. Paint oxidation was observed on six black-on-white specimens out of a total of twenty (30.00%). In addition, red specks resulting from vaporized fire retardant that was aerially dropped in the vicinity of site #1651 was observed at a frequency of 23.08% for artifacts sampled from site #1651. The percentage of artifacts that exhibited no discernable evidence of thermal alteration was 23.36%. Catastrophic forms of thermal alteration such as fracturing, and more benign forms such as combustive residue deposition, are well represented within the overall sample. This is consistent with the data presented for the combined architectural sample, and further supports the general assertion that the selected sites on Wetherill Mesa were burned under severe wildland fire conditions.

CHAPIN MESA AND PARK MESA SITES (2002 Long Mesa Fire)

The Long Mesa Fire burned approximately 2601 acres (1053 ha) in Mesa Verde National Park during late July and early August of 2002. Archaeological fire impact sampling was resumed at the park during the fall of 2002, shortly after the fire had occurred. Six Pueblo I-III habitation sites located on Chapin, West Chapin, and Park Mesas were sampled for fire effects information. Each of the seven sites are located on mesa tops and were situated in a mature piñon-juniper vegetative community prior to the fire. Fire intensity at each of the sampled sites was estimated as severe based on the presence of heavily burned piñon-juniper fuels on each of the mesas.

Important information regarding thermal alteration of archaeological resources recorded at a brief interval following a wildland fire was added to the overall study. It was hypothesized that sooting, defined as loosely adhering combustive residue particles deposited on the surface of archaeological materials, and combustive blackening, defined as combustive residue deposits that strongly adhere to the surfaces of archaeological materials, would be observed at higher frequencies at the 2002 Long Mesa sites compared to sites sampled from 2000 fire areas. Since sampling was conducted shortly after the Long Mesa Fire, combustive residue deposits would not have been significantly reduced due by weathering processes, as was the case for sites sampled two years post-fire. Sooting was not observed during sampling in the 2002 Long Mesa Fire area, and was presumed to have been washed away due to precipitation following the fire. However, combustive blackening of architectural rubble and surface artifacts was observed in significantly greater frequencies, an average of 95%, compared to the 2000 Bircher and Pony Fire area sites that produced frequencies which were negligible for architectural rubble, and were in the 20% range for surface artifacts. This suggests that in a period of as little as two years, the majority of combustive residue deposits may be mitigated due to weathering processes, and that sooting should not be considered a significant form of thermal alteration since these deposits are readily removed from the surfaces of archaeological material with precipitation.

In general, surface architectural rubble exhibited significant levels of combustive blackening, oxidation, and thermal spalling. Surface artifacts from sample areas also exhibited a considerable degree of combustive blackening and oxidative staining, but catastrophic forms of thermal alteration such as thermal fracturing were not observed at great frequencies.

A total of, forty-two individual pieces of architectural rubble derived from Cliff House Formation sandstone were sampled for thermal alteration attributes. Combustive blackening and oxidation were the most pervasive forms of thermal alteration observed for the combined sample, recorded at frequencies of 100.00% and 95.24% respectively. Thermal spalling was also prevalent at 66.67%, yielding an overall percent mass loss estimate of 5.68%. Only three specimens from the combined sample exhibited evidence of thermal fracturing, but the percent mass loss estimate associated with the fracturing was relatively high at 29.60%. The combined percent mass loss estimate for thermally spalled and fractured specimens was calculated at 9.62%. Weather fracturing was not observed among any specimens, presumably due to the short period of elapsed time between the occurrence of the fire and initiation of data collection. Conversely, the average portion of thermal alteration estimate for the overall sample was relatively high at 41%, which is also likely a function of the elapsed time since burning had occurred. Compared to sites sampled from the 2000 burn areas within the park, the 2002 Long Mesa architectural sample exhibited an approximate 90% increase the frequency of combustive blackening; indicating that combustive residue deposits on sandstone architectural materials weather rapidly from the surfaces of affected specimens. Other forms of thermal alteration such as oxidation and thermal spalling are; however, consistent with data collected from the 2000 fire samples, and with what would be expected to occur under conditions of high intensity wildland fire.

The combined surface artifact sample included a total of 136 specimens, comprised of 85.29% pottery sherds, 12.50% lithic materials, and 2.21% architectural materials (daub or adobe). The lithic sample was predominantly comprised of primary and secondary flaking debris (88.24%), representing various types of raw material including chert (47.05%), mudstone (35.29%), and green quartzite (11.29%). Combustive blackening was clearly the most prevalent form of thermal alteration observed for combined sample at a frequency of 95.59%. Oxidative staining was observed at a much lower frequency of 19.85%, as was thermal fracturing (5.15%), paint oxidation (2.94%), heat-induced color change (2.21%), and crazing and spalling (0.74%). However, only two specimens (1.47%) were observed to be unaffected by thermal alteration. The average portion of thermal alteration estimate for the combined sample was calculated at 41%, which is relatively high compared to sites sampled from the 2000 fire areas. Again, this is probably a function of time, considering that the sampling at sites impacted by the 2002 Long Mesa Fire was conducted less than two months post-fire. Overall, the results of artifact sampling are consistent with those reported for the combined architectural sample, and are within the range of observable thermal alteration associated with severe wildland fire conditions.

BATTLESHIP ROCK SITES (1996 Chapin 5 Fire)

The Chapin 5 Fire burned approximately 4781 acres (1935 ha) in portions of Upper Soda Canyon, Little Soda Canyon, School Section Canyon, Park Mesa, Upper Battleship Rock area, and Lower Battleship Rock Area during August of 1996 (Ives et al. 2002). Fire impact sampling at ten Upper and Lower Battleship Rock area Pueblo I-III sites exposed to wildland fire during the Chapin 5 Fire was implemented. The sites sampled during the project are located within heavily charred and combusted piñon-juniper fuels along an extensive canyon slope bench above Soda Canyon near the eastern aspect of Battleship Rock. Based on the extent of heavy fuel combustion and probable pre-fire fuel load, the fire severity assessment for the sample area was recorded as severe. Sampling at selected sites located within this area provided a unique opportunity to collect fire impact data at archaeological sites burned under severe wildland fire conditions nearly 6 years after the fire had occurred. The goal of the research here was to collect information regarding the preservation of thermally altered archaeological resources over time, and the enduring qualities of certain forms of thermal alteration defined in the study.

During the initial survey of fire effects at the selected sites, numerous sandstone architectural blocks were observed with patterned fracturing indicative of mechanical weathering processes in which the original block was fractured into several smaller blocky segments. It is suggested that affected architectural blocks experienced fine thermal fractures resulting from exposure to heat energy during the Chapin 5 Fire, which over time, became susceptible to mechanical weathering processes and subsequent weathering related fracturing. Architectural blocks located within sample units exhibiting this type of fracturing received a thermal alteration code defined as *weather fracturing (WFR)*, and percent mass loss estimates were calculated for each block using the same method implemented for thermally spalled and fractured specimens from more recently burned sites that were sampled during the project. However, there were very few instances of in situ thermal spalling and fracturing observed for the sample. Spall scars were visible on the surfaces of architectural sandstone blocks, but the exfoliated portions had been significantly reduced or displaced by various weathering and hydrologic processes. Therefore, an additional thermal alteration code labeled *spall scarring (SPS)* was defined to addresses the issue of thermally induced spalling and the weathering of in situ spalls over time.

Inconsistencies regarding the extent and degree of thermal alteration were also observed between the artifact and architectural samples. Many of the surface artifacts sampled at the Chapin 5 Fire sites exhibited no evidence of thermal alteration, and most of the thermal alteration observed took the form of oxidative staining and combustive residue deposits. These deposits were generally weather-faded in appearance compared to specimens sampled at sites impacted by the 2000 Bircher and Pony Fires. The disparity between surface artifacts and architectural materials as seen for the Chapin 5 sites may be a function of the elapsed time since burning and the compositional nature and size of architectural blocks compared to midden artifacts. Sandstone architectural blocks are considerably larger and potentially more enduring than smaller dispersed and fragmented surface artifacts; therefore, one might predict that over time thermal alteration attributes would be observed in greater frequencies for architectural feature than surface artifacts. Moreover, surface artifacts included in the sample may only represent a small proportion of the density of the surface scatter at the time of the fire due to erosional processes that may transport or bury artifacts post-fire. Other factors such as the low profile of artifacts at the soil surface, and the potential for sediment to mitigate the effects of heat energy of partially and completely buried artifacts, which are now located at the soil surface, may have contributed to the disparity in fire effects seen between surface artifacts and architectural rubble.

In total, ten Pueblo I-III habitation sites, five within the Upper Battleship Rock area and five within the Lower Battleship Rock Area, that were burned during the 1996 Chapin 5 Fire were sampled for fire effects attributes. The combined architectural sample consisted of seventy-four individual sandstone masonry elements, 98.65% of which were derived from Cliff House Formation Sandstone. The most common form of thermal alteration observed for architectural rubble was red oxidation that affected the upper surfaces of blocks, accounting for approximately 30-50% of the total surface area of each specimen. Oxidation was pervasive, observed at a frequency of 100.00% for the combined sample. The incidence of in situ spalling, observed at a frequency of 20.27%, was limited due largely to the erosion and weathering of exfoliated spalls. However, spall scarring (concave scars on the surface of blocks where spalls have been exfoliated) was observed at a much higher frequency of 59.46% providing further substantiation that a high prevalence of thermal spalling occurred within the sample. The percent mass loss estimate for specimens affected by in situ thermal spalling was calculated at 4.06%. Thermal fracturing (fine linear fractures on surfaces of a specimen, often resulting in fragmentation) was observed at a low frequency, affecting only 4.05% of the combined sample, and yielding a percent mass loss estimate of 20.24%. Weather-induced fracturing (patterned blocky fragments resulting from mechanical weathering processes acting on thermal fractures) of thermally altered architectural rubble was observed at a frequency of 17.57%. Weather-fractured specimens produced a percent mass loss estimate of 21.68%. The combined percent mass loss estimate for thermally spalled, fractured, and weather-fractured specimens was calculated at 18.34%. Combustive blackening was not observed for the combined sample, but no specimen within the sample was unaffected by thermal alteration. The average portion of thermal alteration estimate for the combined sample was rather high at 31%.

The impact of the Chapin 5 Fire on architectural rubble at the selected sites was readily apparent six years post-fire. The thermal alteration of sandstone architectural materials has both immediate and long-term consequences for the preservation of architectural features. Immediate negative effects include thermal spalling and fracturing which destroy the original mass and dimensions of masonry elements. In addition, oxidation alters the mineral structure of affected surfaces and may accelerate weathering of sandstone. Long-term negative effects associated with thermally altered architectural sandstone have been documented in the form of weather-induced fracturing that is believed to occur when physical weathering processes act on thermally altered sandstone with fine fractures, which overtime break in to numerous patterned/blocks fragments. The original mass of architectural elements can be reduced by over 30% due to weather fracturing, compared to only 3-4% due to thermal spalling. Clearly, surface architectural materials within the Battleship Rock area have been significantly impacted by the Chapin 5 Fire, and as a result will continue to be negatively impacted over time due to weathering processes operating on sandstone elements weakened by thermal alteration.

The effects of wildland fire conditions on surface artifacts at the sampled Battleship Rock area sites is less apparent than those discussed above for architectural features. The combined sample of surface artifacts included a total of 232 artifacts comprised of 74.25% pottery sherds (38.13% black-on-white, 34.10 corrugated, and 27.74% grayware), and 24.89% lithics, predominantly chert, quartzite, and mudstone primary and secondary flaking debris. The most common form of thermal alteration observed for the combined artifact sample was weather-faded combustive blackening generally localized on the edges and tips of specimens, which affected 26.72% of sampled specimens. In addition, weather-faded oxidation was observed at a frequency of 7.33%, 3.45% of specimens exhibited thermal fracturing, and paint oxidation of black-on-white sherds was observed for 2.59% of the sample. Two chert specimens exhibited thermal fractures, potlid fracturing, and crazing, representing approximately 10% of chert artifacts. The average portion of thermal alteration estimate for the entire sample was calculated at 21%. However, the majority of artifacts (64.66%) from the combined sample did not exhibit any evidence of thermal alteration, which is inconsistent with what was observed for the overall architectural sample and burn intensity assessments based on environmental data that indicated that the selected sites had experienced severe wildland fire conditions.

Several variable have likely contributed to this disparity and may include: 1) The difference in surface area and material composition of sandstone architectural elements and various types of artifacts; 2) Evidence of thermal alteration has been diminished by weathering; 3) Many thermally altered surface artifacts may have been dispersed vertically and horizontally due to erosion and other natural taphonomic processes; 4) Numerous artifacts included in the sample may have been located subsurface at the time of the fire, which would mitigate the much of the fire impact. Nonetheless, evidence of thermal alteration was still observable six years post-fire indicating that the immediate impact of the fire likely had a significant negative impact on surface artifacts.

LONG CANYON SITES (1989 Long Mesa Fire)

The fire assessment study was also extended to archaeological sites that were impacted by the 1989 Long Mesa Fire. The Long Mesa Fire burned approximately 3000 acres on Long Mesa and bordering canyons in July of 1989 (Eininger 1990). Fire effects sampling of architectural features and surface artifacts on Long Mesa offered a unique opportunity to assess the long-term impact of a wildland fire some thirteen years after it had occurred. The purpose of sampling selected sites from this burn area was to assess the long-term impact of wildland fire on archaeological sites. Specifically, the study was aimed at addressing issues regarding the permanence of different types of thermal alteration, and the effect of fire on artifact and architectural preservation some thirteen years post-fire.

Eininger (1990) provides important background information and a post-fire assessment of archaeological sites impacted by the 1989 Long Mesa Fire. Information from Eininger's report on "fire damage" to affected archaeological sites was categorized into several levels of fire impact; "H = High degree of fire damage", "M = Moderate degree of fire damage", "L = Low degree of fire damage", "N = No fire damage", and "U = Fire damage unknown." This information as well as observations on vegetation type and topographic location was utilized in the present study as important background information from which to assess the long-term impact of the fire on selected sites and to collect data on the resilience of various types of thermal alteration on archaeological materials over time. In addition, each of the nine sites sampled were also located within a wildland fire zone that was burned in 1934; however, no information regarding the impact of the 1934 fire on the sites is available.

Nine Pueblo II-III habitation sites were sampled during this study. All selected sites were situated within mountain shrubland vegetative communities and located on large open canyon slope benches either near the talus slope or near the mesa top. In general, the data collected during sampling in 2002 was consistent with that recorded by Eininger. In total, seventy-four individual sandstone architectural blocks were coded for thermal alteration attributes across the nine sites. The majority (77.03%) of the sandstone was identified as being derived from the Cliff House Formation. The remaining 22.97% of the sample consisted of a light colored, coarse-grained sandstone potentially derived from the Point Lookout Formation. Both types of sandstone appeared to be equally susceptible to the common forms of thermal alteration documented for architectural rubble, such as pink-red oxidation, thermal spalling, and heat-induced weather fracturing. Overall, the thermal alteration data collected from architectural sample units was consistent with the fire damage information provided by Eininger with most of the rubble at selected sites exhibiting a moderate degree of thermal alteration.

Oxidation was the most common form of thermal alteration observed for the combined architectural sample at an observed frequency of 98.65%, although much of it had been diminished to a light pink/red color due to weathering. In situ thermal spalling was observed for 12.16% of the sample, which produced an average percent mass loss estimate of 3.13%. In addition, spall scarring was observed on 63.51% of the rubble sampled. Evidence of thermal fracturing was limited, only affecting 2.7% of the sample. However, weather fracturing was observed at a higher frequency of 21.62% and yielded an average percent mass loss estimate of 17.20%. Weather fracturing and thermal spalling combined produced an average percent mass loss estimate of 18.92% for the overall sample. Only one specimen (1.35%) did not exhibit any observable forms of thermal alteration. Combustive blackening was not observed at any frequency, although it was noted by Eininger (1990) during the initial survey. The combustive residue deposits have been weathered from the surfaces of thermally altered architectural rubble.

The average portion of thermal alteration (percent of specimen surfaces affected by thermal alteration) estimate for the combined sample was 21%. Overall, the sample exhibited pervasive oxidation as well as a notable degree of spalling, observed as in situ spalling and spall scarring. Moreover, the presence of weather-induced fracturing of thermally altered sandstone rubble would further suggest that the effects of heating sandstone may be exacerbated over time due to mechanical and chemical weathering.

The combined artifact sample included 216 surface artifacts, 83.33% of which were ceramic artifacts, and 16.67% lithic artifacts. Corrugated sherds represented 42.13% of the ceramic sample, black-on-white 21.30%, and grayware 11.11%. The majority of lithic artifacts (80.55%) consisted of primary and secondary flaking debris with banded chert/jasper and gray quartzite being the most common material types respectively representing 47.22% and 25.00% of the lithic sample. The most common form of thermal alteration observed for the entire artifact sample was combustive blackening at a frequency of 18.06% followed by oxidative staining at 11.11%. All of the combustive residue deposits and oxidative staining observed was weather-faded and concentrated on edges and tips of artifacts. Paint oxidation, spalling, fracturing, crazing, were negligible with observed frequencies at less than 1%. Overall, 72.69% of the artifact sample lacked any discernable evidence of thermal alteration.

An observed disparity in the degree of thermal alteration between the combined architectural sample and artifact sample exists for the Long Mesa Fire sites. One major consideration is that architectural rubble has a considerably larger surface area and higher profile above the soil surface, which results in exposure to a greater degree of heat energy during a wildland fire. Similar to the 1996 Chapin 5 Fire sites, several other factors that have potentially contributed to the high percentage of artifacts lacking evidence of thermal alteration may include: 1) low to moderate fire intensities near midden areas; 2) the small surface area and low profile of midden artifacts; 3) artifacts at the surface during sampling may have recently eroded to the surface and were subsurface during the fire; 4) thermally altered artifacts may have been eroded away or buried in the midden area; 5) the elapsed time since the fire may diminish observable thermal alteration through various weathering processes.

LONG MESA SITES (1934 Wickiup Point Fire)

Fire impact sampling was performed at four Pueblo I-III habitation sites located on Long Mesa that were burned during the 1934 Wickiup Point Fire. These sites were not burned during the 1989 Long Mesa Fire. The goal of sampling here was similar to that described for the 1989 Long Mesa Fire sites sampled during the study. The issue of thermal alteration permanence and resource preservation was further extended to these sites where exposure to wildland fire occurred some sixty-eight years ago. Indeed, evidence of the fire was observed at the selected sites, but it was almost entirely limited to architectural features, generally taking the form of highly weathered oxidation and limited spall scarring.

The selected sites were located on Long Mesa and a finger ridge above the west fork of Wickiup Canyon. Present day vegetation encompassing the sites consists largely of mountain shrubland species with some dispersed piñon-juniper new growth. It was clear that the area was not burned during the 1989 Long Mesa Fire based on vegetation maturity and the visible boundary that fire had created. It was also evident that the area in with the selected sites were located had experienced wildland fire conditions of some antiquity since several aged dead and down piñon-juniper logs exhibited evidence of charring. In addition, lichen growth was observed on the surfaces of several oxidized sandstone blocks. The assumption was made that the fuels in the vicinity of the selected sites were composed of mixed piñon-juniper and mountain shrub, thus creating the potential for high fire severity.

In total, twenty-six architectural blocks derived from Cliff House Formation sandstone were sampled for thermal alteration attributes. The most prevalent type of thermal alteration observed was highly weathered oxidation, generally limited to the edges and a small portion (10-20%) of the upper surface of architectural rubble. This level of oxidation was observed on twenty-one specimens, or 80.77% of the sample. Additionally, heavily weathered spall scarring was observed on nine specimens (34.62%), and weather fracturing was observed for three (11.54%) thermally altered specimens yielding a percent mass loss estimate of 13.56%. No in situ thermal spalling or fracturing were observed across the entire sample, and four specimens, or 15.38% of the sample did not exhibit any evidence of thermal alteration. The average portion of thermal alteration estimate (portion of surface area affected by thermal alteration) for the combined sample was modest at approximately 9%.

Weather-induced fracturing and surface weathering of thermally altered architectural rubble pose the greatest threat to the preservation of these sites. The overall surface area and mass of affected blocks have likely been reduced as a result of thermal alteration and weathering over time. While specific data is limited, the results of sampling do show that weather-fractured specimens lost an average of 13.56% of their overall mass. Mass loss through thermal spalling also has probably contributed to a reduction in mass among affected specimens. In addition, it is probable that the incidence of thermal spalling, fracturing, and oxidation were observable in considerably higher frequencies immediately after the fire. Oxidation is the most enduring and easily recognizable form of thermal alteration documented for architectural sandstone, even sixty-eight years post-fire.

The impact of the Wickiup Point fire on surface artifacts sampled at the selected sites was not readily discernable. The combined sample included ninety-four artifacts, comprised of 80 (85.11%) pottery sherds and 14 (14.89%) lithics, representing mostly primary and secondary flaking debris. The vast majority of surface artifacts, 95.83%, did not exhibit any evidence of thermal alteration. The only form of thermal alteration observed was a limited degree of highly weathered combustive blackening and oxidative staining on two grayware sherds. In addition, one primary flake located outside of the sample unit at site #1978 exhibited crazing as well as a minimal degree of weathered combustive blackening. Several factors have probably contributed to the low incidence of observed thermal alteration on the artifact sample. These include; the sixty-eight year elapsed time period since the fire, various weathering processes, and the size and material composition of surface artifacts compared to larger and higher profile architectural rubble. Certainly the incidence of thermal alteration of surface artifacts would have been much higher if sampling was conducted immediately following the fire; however, the important consideration to make is that some evidence of the fire could be observed nearly seventy years post fire, and that its impact continues to affect surface artifacts due to exposure to weathering.

SUMMARY AND CONCLUSIONS

In total, 72 Pueblo I-III open-air habitation sites were sampled during the fire effects study conducted at Mesa Verde National Park. The Ancestral Pueblo sites included in the sample were burned during several different wildland fires that occurred at various time intervals, to include the 2002 Long Mesa, 2000 Bircher and Pony, 1996 Chapin 5, 1989 Long Mesa, and 1934 Wickiup Point fire areas. Archaeological sites included in the overall sample were also located within variety of fuel types including mixed grass/shrub, mountain shrub, and piñon-juniper as well as topographic locations to include canyon bottoms, canyon slopes and mesa tops. Overall, the architectural and artifact sample units produced a combined sample of 595 sandstone masonry elements and architectural rubble fragments, and 1653 surface artifacts predominantly comprised of pottery sherds and lithic debitage.

Thermal alteration counts and frequencies for the overall architectural sample are listed in Table 5.2.

Table 5.2: Thermal alteration frequency of sampled architectural blocks: Combined sample (n=595)

TH Type	CC/OX	CB	SP	SPS	FR	WFR	NO	% Loss
Count	574	66	240	104	26	32	20	10.08% Total
Percentage	96.47	11.09	40.34	17.48	4.37	5.38	3.36	3.51% SP 22.74% FR 18.94% WFR

The results from the architectural sample units show that the most common form of thermal alteration recorded during the study was oxidation (CC/OX) at an observed frequency of 96.47%. The exact processes involved in the oxidation of architectural blocks derived from local sandstone (predominantly Cliff House Formation) at Mesa Verde has not been investigated from a mineralogy perspective; however, preliminary research suggests that the reddening occurs via the oxidation of limonite [FeO(OH)] to hematite [Fe2O3] (personal communication Philip Cloues 2003). The results of experimentation show that oxidation of Cliff House Formation sandstone is initiated at approximately 300°C and become more pervasive as temperatures at the surface of the stone increase. Thermal spalling (SP) was observed for 40.34% of the overall sample, and interrelated spall scaring (SPS) was recorded for 17.48% of specimens in which in situ thermal spalls were not observed. In situ thermal spalling was attributed to an estimated 3.51% loss in mass of affected specimens due to the exfoliation of the spalls. Thermal spalling of architectural blocks has an immediate negative impact on Pueblo architecture at Mesa Verde. Thermal spalling is induced by thermal stress that exceeds the tensile strength of the sandstone whereby a combination of factors such as thermal expansivity, thermal diffusivity, and steam pressure cause thermal spalling and fracturing (Freeman et al. 1972; Hettema et al. 1998; Marovelli et al. 1966; Wai et al. 1982). During the experiment in Chapter 4, thermal spalling of Cliff House Formation sandstone was initiated at 300-400°C, and became more pronounced as specimen surface temperature increased beyond this range. Thermal fracturing (FR) was observed for 4.37% of the overall sample of architectural rubble, and contributed to an estimated 22.74% loss in the pre-fire mass of affected specimens. Thermal fracturing of Cliff House Formation sandstone was experimentally replicated when specimens surface temperatures reached the 400-500° and above (up to 700°C) (Chapter 4). The data generated during experimentation regarding thermal alteration of Cliff House Formation sandstone suggest that, surface temperatures during wildland fires at Mesa Verde probably ranged between 300-700°C+, depending on fuel type and burn severity. In addition, heat-induced weather fracturing (WFR) affected 5.58% of the overall sample, and yielded a percent mass loss estimate of 18.94%. Thermal spalling, thermal fracturing, and weather fracturing combined produced an estimated overall loss in mass of 10.08% among affected specimens. Percent mass loss estimates were attained by adding the total weight of spalls and fragments from an individual block to estimate the amount of mass a block as lost due to spalling or fragmentation. The weight of the spalls and fragments are divided by the weight of the block and multiplied by 100 to derive a percent loss estimate.

The average number of spalls recorded per specimen was 7, and the average combined weight of those spalls was 374g. Although thermal spalling was often observed to affect between 20-30% of the surface area of the architectural specimens, the spalls themselves were relative small in diameter and thin compared to the larger fragmented portions of specimens affected by thermal fracturing and weather fracturing. On average, 1.5 fragments weighing an average of 1472g were recorded for specimens exhibiting thermal fracturing, and an average of 2 fragments with a combined average weight of 1237g were recorded for weather fractured specimens. Therefore, weather fracturing and thermal fracturing are associated with significantly greater percent mass loss estimates (18.94-22.74%) compared to thermal spalling (3.51%) where only a portion of the upper surface of the sandstone architectural element is exfoliated due to thermal stress.

Combustive blackening (CB) was recorded at an observed frequency of only 11.09% for the overall architectural sample. The incidence of combustive blackening of sandstone architectural elements seems to diminish over time with exposure to weathering since combustive blackening was prevalent on specimens sampled from the 2002 Long Mesa fire area, but virtually nonexistent at sites burned during the 1996, 1989, and 1934 fires. However, only 3.27% of the overall sample exhibited no (NO) evidence of thermal alteration. The most important observation is that nearly the entire sample showed evidence of oxidation, suggesting that oxidation occurs at low, moderate, and high fire intensities, and that the reddening caused by the oxidation of limonite to hematite is a lasting form of thermal alteration for sandstone architectural elements. In addition, over 40% of the overall sample exhibited thermal spalling, which accounted for an average loss in mass of 3.51%. The high incidence of oxidation combined with the prominence of thermal spalling suggest that architectural blocks derived from local sandstones (predominantly Cliff House Formation Sandstone) are quite vulnerable to the adverse effects of heat-induced damage resulting from exposure to wildland fire.

Thermal alteration frequencies and counts for the combined artifact sample are provided in Table 5.3.

Table 5.3: Thermal alteration frequency of sampled artifacts: Combined sample (n=1653)

TH Type	**CC/OX**	**CB**	**CC**	**POX****	**FR**	**SP**	**CZ***	**PL***	**NO**
Count	276	619	22	32	79	53	13	18	806
Percentage	16.70	37.45	1.33	6.90	4.78	3.21	9.22	12.77	48.76

* Chert artifacts only *(crazing and potlid fracturing)* ** Black-on-White sherds only *(paint oxidation)*

In total, 1653 surface artifacts sampled primarily from midden contexts were coded for thermal alteration attributes during the study. Pottery sherds were the most prevalent type of artifact recorded, comprising 73.80% of the overall sample. Corrugated sherds made up 46.61% of sherd sample, black-on-white sherds 37.42%, and grayware sherds 15.97%. Lithic artifacts represented 24.43% of the combined sample with cherts comprising 34.81% of those artifacts, mudstone 28.64%, and quartzite 26.67%. Lithic artifacts consisted largely of primary and secondary flaking debris, 41.34% and 28.96% respectively.

The results of thermal alteration coding from the artifact sample units indicate that the most common form of thermal alteration observed was combustive blackening (CB) (generally observed on the upper edge of a specimen), affecting 37.45% of artifacts sampled. Oxidative staining (CC/OX) (generally observed on the upper edge of a specimen in the form of oxidized sediment, orange-brown in color) was recorded at an observed frequency of 16.70%. Thermal fracturing (FR) was observed for only 4.78% of sampled artifacts, and thermal spalling (SP) was also observed at a low frequency of only 3.21%. Other forms of catastrophic thermal alteration such as potlid fracturing (PL) and crazing (CZ) only affect chert artifacts, and were observed at frequencies of 9.22% and 12.77% among sampled chert artifacts. Heat-induced color change (CC) (color change due to mineral oxidation) was observed for 1.33% of the overall sample (generally limited to lithics). In addition, paint oxidation (POX) is a form of thermal alteration that only affects the black painted designs on black-on-white sherds, and was observed at a frequency of 6.90%.

An important consideration for the combined artifact sample is the high percentage of artifacts (48.76%) that did not exhibit any discernable evidence of thermal alteration (NO). This proportion is considerably higher than the 3.36% of sandstone architectural elements that did not exhibit any evidence of thermal alteration. Several factors may have contributed to this obvious divergence including: 1) The difference in surface area, surface profile, and material composition of sandstone architectural elements and compared to various types of artifacts positioned at the soil surface; 2) Evidence of thermal alteration on surface artifacts has been more readily diminished by weathering processes compared to architectural sandstone elements; 3) Many thermally altered surface artifacts may have been dispersed due to erosion and vertical movement due to natural processes, and therefore were not present during data collection; 4) Numerous artifacts included in the sample units may have been located subsurface at the time of the fire, which would mitigate the much of the fire impact. 5) Thermal stress affects sandstone elements more pervasively than the lithic and ceramic material represented in the artifact samples.

In addition to thermal alteration counts and frequencies for the overall architectural and artifact samples, counts and frequencies by wildland fire date were also generated. Sample unit data from the 2002 Long Mesa, 2000 Fires Sites (Bircher and Pony Fires), 1996 Chapin Fire, 1989 Long Mesa Fire and the 1934 Wickiup Point Fire were compared to observe any potential differences in the frequency of thermal alteration attributes over time. These data are listed below in Table 5.4.

Table 5.4: Thermal alteration of sampled architectural blocks by fire date

TH Type	CC/OX	CB	SP	SPS	FR	WFR	NO	% Loss
Long Mesa 2002 (N=6) n=42	42 100.00	40 95.24	28 66.67	0 0	3 7.14	0 0	0 0	9.62% Total 5.68% SP 29.69% FR
2000 Fire Sites (N=43) n=396	381 96.21	26 6.57	205 51.77	3 0.76	10 2.53	0 0	15 3.79	7.09% Total 4.43% SP 22.39% FR
Long Mesa 1989 (N=9) n=75	73 98.65	0 0	9 12.16	47 63.51	2 2.70	15 20.27	1 1.35	18.92% Total 3.13% SP 17.21% WFR
Wickiup Point 1934 (N=4) n=26	21 80.77	0 0	0 0	9 34.62	0 0	3 11.54	4 15.38	12.14% Total 12.14% WFR (WFR only)

The most common form of thermal alteration observed on architectural blocks across all sites was oxidation; 100% for the 2002 Long Mesa sample, 96.21% for the 2000 Fires sample, 100% for the 1996 Chapin 5 sample, 98.65% for the 1989 Long Mesa sample, and 80.77% for the 1934 Wickiup Point sample. These data indicate that the oxidation of architectural blocks is both a highly prevalent and long lasting form of thermal alteration. Oxidation of blocks from the 1934 Wickiup Point sample was observed in nearly the same frequency of the other sites in the sample, some 68 years after the fire occurred. Conversely, combustive residue blackening does not seem to be a lasting from of thermal alteration since its frequency drops off precipitously over time. A high percentage of combustive blacking (95.24%) was observed in the 2002 Long Mesa Sample, but was only observed in 6.57% of the 2000 Fires sample and at 0% for the remainder of the sample. This suggests that over time combustive residue deposits begin to weather rapidly from the surface of architectural blocks. The prevalence of spalling was greatest for the 2002 Long Mesa (66.67%) and 2000 samples (51.77%). The prevalence of spalling in the older samples gradually diminished from 20.27% for the 1996 Chapin 5 sample to 12.16% for the 1989 Long Mesa sample, and 0% for the 1934 Wickiup Point sample. The reduced frequency of observed in situ spalling for samples over time is likely due to weathering and erosion of spalls. However, the frequency of fracturing due to weathering processes increased with time with the 1996, 1989, and 1934 samples showing values of 18.92%, 20.27%, and 11.54% respectively. No weathering related fracturing was observed at sites from the 2002 and 2000 samples. Although the presence of spalls was limited in the older sites, the incidence of fracturing related to weathering processes was a contributing factor in the percent loss estimates for those sites. The percent loss estimates for the 1996 sample was 16.32%, and the 1989 and 1934 samples were 22.15% and 13.56%. The percent loss estimates for the 2002 and 2000 samples were lower at 11.28% and 7.82%, despite the presence of in situ spalls and small fragments. This indicates that percentage loss estimates for the older sites likely represent a minimum estimate of mass loss for architectural blocks since the majority of associated spalls had been weathered or eroded away prior to sampling. More importantly, this suggests that an architectural block may not only lose a significant portion of its mass and original dimensions due to the immediate effects of thermal alteration via spalling and fracturing, but may also be more significantly affected over time due to weathering processes. The end result is that over a period as little as 4 years, thermally altered architectural blocks may become significantly diminished in mass and dimension.

Artifact thermal alteration data for the sites by fire date are provided in Table 5.5.

Table 5.5: Thermal alteration frequency of sampled artifacts by fire date

TH Type	CC/OX	CB	CC	POX	FR	SP	*CZ	*PL	NO
Long Mesa 2002 (N=6) n=136	27 19.85	130 95.59	3 2.21 *37.50	4 21.05	7 5.15	1 0.74	1 *12.50	0 0.00	2 1.47
2000 Fire Sites (N=43) n=847	190 22.43	325 38.37	15 1.77 *23.45	20 9.00	46 5.43	38 4.49	8 *12.50	9 *14.06	356 42.03
Chapin 5 1996 (N=10) n=232	17 7.33	62 26.72	0 0.00	6 15.80	8 3.45	2 0.86	2 *9.52	2 *9.52	150 64.66
Long Mesa 1989 (N=9) n=216	24 11.11	39 18.06	0 0.00	1 2.17	1 0.46	1 0.46	1 *5.00	2 *10.00	157 72.69
Wickiup Point 1934 (N=4) n=94	2 2.13	0 0.00	2 2.13 *100.00	0 0.00	0 0.00	0 0.00	0 0.00	0 0.00	92 97.87

* Chert specimens only

The most common type of thermal alteration for the artifact sample units compiled by fire date is combustive blackening. The prevalence of combustive blackening was greatest for the 2002 sample (95.59%); and tapered off for the older samples; 2000 (38.37%), 1996 (26.72%), 1989 (18.06%), 1934 (0%). Unlike the sandstone architectural block, combustive blacking is a lasting form of thermal alteration on artifacts. Typically, combustive blackening was observed on 20-30% of the surface area of an artifact, usually on its upper edge. The combustive residue deposits probably weather quickly from the relative soft and porous surface of sandstone architectural blocks; however, combustive residue deposits may penetrate and adhere to the surfaces of common artifacts such as pottery sherds more resiliently. The deposits on artifacts do, however, seem to diminish over time judging by the consistent reduction in frequency chronologically from 95.59% in the 2002 sample to 0% in the 1934 sample.

Oxidative staining was the second most prevalent form of thermal alteration observed for sampled artifacts. The frequency of oxidation was lower than that observed for combustive blackening varying between 22.43% (2000 sample) to 2.13% (1934 sample). This form of thermal alteration seems to be less common, but more enduring than combustive blackening. It was usually observed as an orange-brown hue on 20-30% of the upper surface and edge of an artifact (most prevalent on pottery sherds), and is believed to result from oxidation of sediment that adhered to the artifact prior to burning. The only other notable form of thermal alteration was thermal fracturing with 5.15% of the 2002 sample, 5.43% of the 2000 sample, and 3.45% of the 1996 sample showing evidence of fracturing. Thermal fracturing was most prevalent for lithic artifacts, particularly chert materials.

The forms of thermal alteration defined for the study that are specific to chert artifacts include crazing and potlid fracturing. Crazing was recorded at an observed frequency of 12.50% for the 2002 sample, 12.50% for the 2000 sample, 9.52% for the 1996 sample, 5.00% for the 1989 sample, and 0.00% for the 1934 sample. Potlid fracturing was observed for 0.00% of the chert artifacts in the 2002 sample, 14.06% for the 2000 sample of chert specimens, 9.52% for the 1996 chert sample, 10.00% for the 1989 chert sample, and 0.00% for the 1934 sample in which no chert specimens were affected. Heat-induced color changes produced alterations in the mineralogy of cherts was recorded at an observed frequency of 37.59% among the 2002 sample of chert artifacts, 23.45% for the 2000 chert sample, 0.00% for the 1996 and 1989 samples, and 100.00% for chert artifacts sampled at the

1934 fire area (only two chert artifacts total). Based on the data collected during the present study, it is suggested that lithic artifacts manufactured from cherts are more highly prone to the adverse effects of expose to heat energy compared to other lithic and artifact classes.

The presence of discernable forms of thermal alteration on common artifact classes consistently diminishes over time as various weathering processes affect artifacts located at the soil surface. The observed frequency of artifacts that were recorded as being unaffected by thermal alteration increased significantly as the time since burning at the selected sites increased. For the 2002 sample, only 1.47% of artifacts were coded as being unaffected by any form thermal alteration. That percentage increased to 42.03% for the 2000 sample, 64.66% for the 1996 sample, 72.69% for the 1989 sample, and 97.87% for the 1934 sample. This suggests that common forms of thermal alteration that affect artifact surfaces such as combustive blackening and oxidation probably become significantly reduced by weathering processes over time. In addition, other more destructive forms of thermal alteration such as thermal fracturing, spalling, and crazing probably become increasingly difficult to observe over time due to erosion, movement due to fluvial processes, and scattering due to many natural factors affecting the uppermost 5cm taphonomic zone of soil.

In order to examine the relationship between fire severity, fuel type, and site location; 49 sites from the 2002 Long Mesa Fire, 2000 Bircher Fire, and 2000 Pony Fire were categorized by fuel type and topographic site location. Sites characterized by Piñon-Juniper fuels and localities on mesa tops were combined to form the *Mesa Top Sites* sample (N=18). Sites located on canyon slopes and benches within Piñon-Juniper fuels, were combined into the *Canyon Slope Sites* sample (N=15). Sites located within canyon bottoms or at the lower margins of canyon slopes and characterized by mixed fuels (sparse Piñon-Juniper, Oak, Shrub, and grasses) were categorized into *Canyon Bottom Sites* sample (N=16). It was suggested that fuel type and slope would be significant factors in determining overall site burn severity and the subsequent thermal alteration of archaeological materials located at soil surface. Sites located within Piñon-Juniper fuels experienced high burn severity regardless of their topographic location on mesa tops or canyon slopes. Sites located at or near canyon bottoms within mixed fuels were observed to have experienced moderate burn severity. The relationship between fuel type/load and observed fire severity at the sampled sites is clear. Dense Piñon-Juniper fuels have a greater impact on archaeological sites in terms of fire intensity and the proportion of potential radiant heat energy transferred to the soil surface compared to sparser mixed fuels that have lesser potential energy output during combustion. The relationship between topographic location of sites and fire severity, however, is not as straightforward. Sites within Piñon-Juniper fuels on mesa tops and canyon slopes were all categorized under high fire severity, while those near the canyon bottom within mixed fuels were recorded as moderate burn severity.

The relationship between fuel type/load and observable thermal alteration of archaeological materials is also important. Architectural and artifact sample units at sites located within areas of Piñon-Juniper fuels showed higher frequencies of thermal alteration compared to sample units within mixed fuel areas. Thermal alteration counts and frequencies for architectural and artifact sample units are provided in Table 5.6.

Table 5.6: Thermal Alteration Frequency of Sampled Architectural Blocks (2002 and 2000 Fire Areas) by Topographic Location and Fuel Type

TH Type	CC/OX	CB	SP	SPS	FR	WFR	NO	% Loss
Mesa Top Sites (PJ) (N=18) n=137	137 100.00	41 29.93	105 76.64	0 0	10 7.30	0 0	0 0	8.11% Total 4.93% SP 25.94% FR
Canyon Slope Sites (PJ) (N=15) n=152	149 98.03	17 11.18	99 65.13	0 0	9 5.92	0 0	3 1.97	6.58% Total 5.12% SP 24.30% FR
Canyon Bottom Sites (mixed) (N=16) n=151	138 91.39	8 5.30	29 19.21	3 1.99	1 0.66	0 0	13 8.61	5.36% Total 3.78% SP 47.40% FR* (one specimen)

In general, sites included in the Canyon Bottom sample showed the lowest proportion of thermal alteration for architectural blocks within sample units compiled by topographic location and fuel type. The Canyon Bottom sample showed the greatest percentage of architectural blocks not impacted by any form of thermal alteration at 8.61%, while the Canyon Slope and Mesa top samples showed considerably fewer unaffected blocks at observed frequencies of 1.97% and 0% respectively. Oxidation was the most prevalent and most evenly distributed form of thermal alteration for all three samples. The Canyon Bottom sample showed the lowest prevalence of oxidation at 91.39% followed by Canyon Slope sites at 98.03%, and Mesa Top Sites at 100%. However, the Mesa Top and Canyon Slope samples showed considerably higher frequencies of thermal spalling (76.64% and 65.13%) and thermal fracturing (7.30% and 5.92%) compared to the Canyon Bottom sample (19.21%) and (0.66%) respectively. Combined percent loss estimates attributed to thermal spalling and fracturing were also greater for the Mesa Top and Canyon Slope samples compared to the Canyon Bottom sample (8.11% and 6.58% vs. 5.36%). This suggests that the Mesa Top and Canyon slope samples experienced greater fire intensity and radiant heat exposure, which induced significant thermal spalling and minor fracturing of architectural blocks. This may also suggest that oxidation (mineral alteration within the sandstone) may preclude thermal spalling and fracturing when blocks are exposed to radiant heat energy since oxidation was ubiquitous among the three samples, but thermal fracturing and spalling were not. This was demonstrated empirically during the secondary Cliff House Formation sandstone experiment conducted in Chapter 4.

The frequency of combustive blackening was greatest for the Mesa Top sample at 29.93%, followed by 11.18% for the Canyon Slope sample and 5.30% for the Canyon Bottom sample. The occurrence of combustive blackening is greatest for the Mesa Top sample largely due to the fact that the sample contained 6 sites from the recent 2002 Long Mesa Fire. The high prevalence of combustive blackening recorded from those sites have skewed the combined Mesa Top sample somewhat toward a higher frequency of combustive deposits. However, combustive residue deposits on architectural blocks in general are not a significant form of thermal alteration compared to oxidation and spalling, and it appears that these deposits weather rapidly since the incidence of combustive residue deposits was much lower for sites burned in 2000 compared to those burned in 2002.

Similar to what was observed for the architectural block sample units, the Canyon Bottom artifact sample exhibited the greatest overall proportion of artifacts not affected by any form of thermal alteration at 61.03%. Artifact thermal alteration data for sites grouped by topographic location are summarized in Table 5.7.

Table 5.7: Thermal Alteration Frequency of Sampled Artifacts (2002 and 2000 Fire Areas) by Topographic Location and Fuel Type

TH Type	CC/OX	CB	CC	POX	FR	SP	CZ	PL	NO
Mesa Top Sites (N=18) n=415	56 13.49	279 67.23	15 3.61 *38.46	11 14.10	31 7.47	22 5.30	3 7.69	8 20.51	91 21.93
Canyon Slope Sites (N=15) n=344	113 32.85	143 41.57	2 0.58 *5.13	11 11.22	34 9.88	19 5.52	4 10.26	5 12.82	101 29.36
Canyon Bottom Sites (N=16) n=349	64 18.34	93 26.65	5 1.43 *27.78	3 4.62	5 1.43	9 2.58	3 16.67	1 5.56	213 61.03

* Chert Specimens Only

Considerably fewer artifacts were recorded as being unaffected by thermal alteration among the Mesa Top and Canyon Slope samples with percentages of 21.93% and 29.36%. Combustive blackening was the most common form of thermal alteration observed for all three samples with percentages ranging between 67.23%-26.65%. Again, the Mesa Top sample showed a disproportionately high prevalence of combustive residue deposits due to the inclusion of sites from the 2002 Long Mesa Fire. Oxidation was also a common form of thermal alteration observed across all samples with percentages ranging from 32.85% to 18.34%. Oxidation and combustive residue deposits may, however, be considered a somewhat benign form of thermal alteration since both seem to weather away or become reduced over time.

More damaging forms of thermal alteration such as fracturing and spalling were observed in higher frequencies for the Mesa Top and Canyon Slope samples with percentages of 7.47-5.30% and 9.88-5.52% compared to considerably lower percentages of 1.43-2.58%

for the Canyon Bottom sample. Potlid fracturing, a form of thermal alteration specific to chert artifacts was also recorded at higher frequencies for the Mesa Top (20.51%) and Canyon Slope (12.82%) samples compared to the Canyon Bottom sample (5.56%). Crazing, also specific to chert, was recorded at a frequency of 7.69% for the Mesa Top sample, 10.26% for the Canyon Slope sample, and 16.67% for the Canyon Bottom sample. The reason for the higher incidence of crazing among chert artifacts within the Canyon Bottom sample is unclear, perhaps due to sample size. Paint oxidation of black-on-white sherds was also observed at greater frequencies for the Mesa Top (14.10%) and Canyon Slope (11.22%) compared to the Canyon Bottom sample (4.62%).

The important observation regarding the comparison of thermal alteration frequencies between samples combined by fuel type and topographic location is related to the critical role fuel load plays in determining fire intensity and subsequent impact on archaeological resources. As was suggested for the architectural block samples, artifact sample units located on mesa tops and canyons slopes experienced high fire severity and exposure to greater levels of radiant heat energy compared to the lesser impacted units located within canyon bottoms. Slope is an important factor in fire behavior, but fuel type/load seems to be the most important variable for the sites sampled in this study. It was suggested that slope would be an important variable in producing severe fire intensity and significant damage to archaeological resources since slope is a key component of severe wildland fire behavior. However, the data compiled during the present study show little difference in thermal alteration frequencies within the artifact and architectural samples between sites located with in canyon slope/piñon-juniper and mesa top/piñon-juniper contexts. Without quantitative data regarding fire behavior and heat energy output it is difficult to ascertain with any certainty potential differences in fire severity between the canyon slope and mesa top contexts.

For the purpose of examining the potential for differential frequencies of thermal alteration between common lithic types and pottery types recorded during the study, lithics were divided into three groups and compared for differences in thermal alteration frequencies, as were pottery specimens. Lithics were divided into three groups consisting of mudstone, quartzite, and chert. Pottery sherds were divided into three groups as well consisting of black-on-white, corrugated, and grayware. Thermal alteration frequencies were compared across lithic types and across pottery type to identify any significant differences within each artifact class. Thermal alteration frequencies for grouped lithic types and pottery types are provided in Table 5.8.

Table 5.8: Thermal alteration frequency of sampled lithic artifacts (All Sited Combined)

TH Type	CC/OX	CB	CC	FR	SP	CZ	PL	NO
Mud Stone N=116	0 0	21 18.10	0 0	10 8.62	1 0.8	0 0	0 0	93 80.17
Quartzite N=108	3 2.77	26 24.07	0 0	7 6.48	5 4.63	0 0	0 0	75 69.44
Chert N=141	8 5.67	36 25.53	13 9.22	35 24.82	1 0.7	13 9.22	17 12.06	55 39.00

Based on the data presented above, chert artifacts are most prone to the effects of radiant heat energy. Only 39.00% of the chert sample was observed to be unaffected by thermal alteration compared to the mudstone and quartzite samples in which 74.4% and 64.66% of specimens were not impacted by exposure to wildland fire. Across all categories of thermal alteration, except thermal spalling, chert specimens showed greater frequencies of thermal alteration compared to the other lithic types. Cherts were more prone to thermal fracture, oxidative staining, and combustive blackening compared to the other lithic material categories. Forms of thermal alteration specific to chert such as heat-induced color change produced by mineralogy alteration, potlid fracturing and crazing were also recorded at notable frequencies (9.22%, 12.06%, and 9.22% respectively).

Combustive deposits were the most common form of thermal alteration across all lithic types, but again, this is fairly benign form of thermal alteration. Thermal fracturing was the second most common form of thermal alteration observed for all lithic categories ranging between 6.48% for quartzite, 8.62% for mudstone, and 24.82% for cherts. Although all lithic types sampled seem to be subject to thermal fracturing, chert is clearly the most susceptible to the differential thermal stress that induces thermal fracturing. Chert specimens were often observed thermally fractured into multiple pieces of irregular and blocky fragments during field recording. Quartzite exhibited the highest frequency of thermal spalling at 4.31%. Thermal spalling among quartzite specimens was similar to that recorded for individual sandstone architectural elements in that the spalls were proportionally large and long, seeming to follow the contour of the stone surface as the spall was exfoliated. Potlid fracturing in chert is somewhat similar in that a portion of the specimen's surface is exfoliated, however the potlid fracture is round and the exfoliated portion is convex on the medial side whereas spalls are typically concave on the medial face. This is likely due to the larger size of quartz crystals present in quartzite and sandstone as compared to cherts. In Chapter 4, thermal fracturing of quartzite and chert specimens was consistently observed where specimens were heated to 450-600°C, suggesting that wildland fires at Mesa Verde generated sufficient radiant heat energy to heat lithic artifacts to this temperature range. Oxidative staining was observed for quartzite and chert specimens at low frequencies and not at all among mudstone specimens. This is likely due to the fact that oxidation is considerably easier to observe on lighter colored cherts and quartzite compared to the virtually black mudstone specimens.

There were no clear-cut differences in thermal alteration frequencies among the pottery groupings. Thermal alteration data for pottery sherd groupings are summarized in Table 5.9.

Table 5.9: Thermal alteration frequency of sampled ceramic artifacts (All Sited Combined)

TH Type	CC/OX	CB	SP	POX†	FR	NO
Black-on-White N=464 (350)	93 20.04	184 39.66	29 6.24	31 8.86	8 1.72	194 41.81
Corrugated N=578	128 22.15	236 40.83	14 2.42	0 0	13 2.25	272 47.06
Grayware N=198	25 12.62	100 50.50	3 1.52	0 0	3 1.52	88 44.44

†Black-on-white sherds only, N=350 B/W sherds recorded with paint, N=114 whiteware specimens

Black-on-white, corrugated, and grayware specimens showed similar frequencies across all types of thermal alteration with the exception of paint oxidation and thermal spalling among black-on-white sherds. Paint oxidation was limited to black-on-whites specimens only due to the fact that this type of alteration does not affect pottery types that typically are not decorated with pigment. Paint oxidation was observed on 8.86% of the black-on-whites specimens, and typically consisted of mineral black pigment being oxidized to a reddish color, or organic black pigment being nearly completely combusted from the surface of a sherd leaving only a slight shadow of the original design. The frequency of thermal spalling of black-on-white sherds was 6.24% compared to the 2.42% and 1.52% values for corrugated and grayware sherds. A small portion of the white slip on black-on-white specimens was often observed exfoliated from the body of the sherd, but specimens were only recorded as exhibiting spalling if the exfoliated portion was found in situ near the sherd. By virtue of their design and composition, black-on-white pottery sherds have the potential to be affected more significantly by exposure to wildland fire since the white slip seems to be susceptible to thermal spalling, and the black pigment can be susceptible to combustion or oxidation.

Combustive blackening (39.66%-50.50%) and oxidative staining (12.62%-22.25%) were the most common forms of thermal alteration observed across all three pottery types. Although combustive blackening was observed at the highest frequency for grayware sherds, it was the black-on-white sherds that were impacted most significantly by this form of thermal alteration. The designs on black-on-white sherds were often observed to be completely or partially obscured by combustive residue deposits. These deposits may wear down over time due to weathering processes; however, typological classification of affected black-on-white sherds may be impeded for several years post-fire, perhaps indefinitely. In general, however, pottery sherds seem to be fairly resistant to thermal alteration since between 41.81%-47.06% of the sample was observed to exhibit no discernable forms of thermal alteration.

Based on the data presented here, wildland fire at Mesa Verde National Park should be considered as an important regional level site formation process that has immediate and long-term implications for the interpretation, and most notably the preservation of archaeological resources at the park. Overall, the results of the thermal alteration data analysis presented above indicate that oxidation, spalling, and associated weathered fracturing of architectural blocks are the most pervasive, enduring, and potentially damaging forms of thermal alteration that affect sites impacted by wildland fire at Mesa Verde National Park. The most important consideration for the sites burned greater than 6 years ago is weather-induced fracturing whereby physical and chemical weathering processes act upon thermally altered sandstone architectural elements (probably within fine thermal fractures induced by thermal stress at the time of burning). This suggests that thermal alteration of blocks seems to exacerbate susceptibility to fracturing and deterioration resulting from weathering processes (chemical and mechanical). An architectural block may not only lose a portion of its mass and original dimension due to the immediate effects of thermal alteration via spalling and minor fracturing, but may also be more significantly affected over time due to weathering processes. In addition, thermal alteration of artifacts can influence their interpretive value in instances where the artifact is fractured or otherwise altered form its pre-fire form. More damaging forms of thermal alteration such as thermal fracturing, thermal spalling, potlidding, and crazing were generally limited to lithic artifacts, cherts in particular. Although not specifically addressed during the study, additional transformations related to soil oxidation, stump and root combustion, bone burning, dendrochronology, thermoluminescence and archaeomagnetic dating, and overall site interpretation may also be confounded by wildland fire (Conner et al. 1989; Conner and Canon 1991; Lentz et al. 1996; Traylor et al. 1990).

Figure 5.1: Oxidation and thermal spalling of Cliff House Formation sandstone.

Figure: 5.2: Weathered fracturing of Cliff House Formation Sandstone (6yrs post-fire)

Figure 5.3: Sherd oxidation/oxidative staining and combustive residue deposition.

Figure 5.4: Thermal spalling of black-on-white sherd.

Figure 5.5: Lithic thermal fracture.

Figure 5.6: Thermal fracture and potlid fracture of chert.

CHAPTER 6
SUMMARY AND CONCLUSIONS

This project was focused on assessing the potential impacts of prescribed and wildland fire on archaeological resources. The research design was divided into three major components: 1) Field-based experimentation performed in conjunction with several different prescribed burning programs representing a variety of fuel types; 2) Laboratory experimentation comprised of both muffle furnace heating trials, and wildland fire simulations conducted in a large wind tunnel; 3) Field-based fire effects sampling of archaeological sites that had been burned during various wildland fires at Mesa Verde National Park. The general purpose of this research was to document the conditions under which significant thermal alteration of archaeological materials occurs under natural fire scenarios. In addition, the field research at Mesa Verde National Park further extended the research objectives to assess the role of wildland fire as a site formation process affecting the immediate and long-term preservation of the archaeological record.

The results of a several laboratory and field based experiments indicate that the important variables to consider when assessing the potential impact of natural fire on archaeological resources include: 1) fuel load; 2) fire behavior; 3) peak temperature and duration of heating; 4) proximity of artifacts to fuels; and 5) class of artifact. Figure 6.1 summarizes the basic fundamentals regarding the thermal alteration of archaeological materials. During combustion, the fire initiates the process as the energy source where the artifact represents the body in which energy is absorbed. The amount of heat energy released during combustion is dependent on the amount of available energy derived from the fuel source, and is influenced by rate and duration of combustion. The amount of energy absorbed by an artifact is a function of energy and is influenced by the thermal conductivity of the artifact material. The resultant thermal alteration of an artifact is a function of temperature/flux multiplied by duration combined with the thermal properties and compositional structure of an artifact where important variables include the coefficient of thermal expansion, thermal conductivity, and tensile strength of an artifact.

Figure 6.1: Fundamentals of artifact thermal alteration.

ENERGY SOURCE → ***ENERGY SINK***
(Fire) **(Artifact)**

ENERGY RELEASED **= Available Energy (Fuel) x Rate x Duration**

ENERGY ABSORBED **= *ƒ*(Energy) + Thermal Conductivity of Material**

THERMAL ALTERATION **= *ƒ*(Temperature/Flux x Duration) + Thermal Properties and Compositional Structure of Artifact [coefficient of thermal expansion, thermal conductivity, and tensile strength]**

The prescribed fire experiments conducted during the project illustrate the importance of fuel type and load in affecting the degree of observable thermal alteration of experimental artifacts. The experiments were performed under a variety of fuel models to include mixed grass prairie, mixed grass prairie / ponderosa pine, mixed conifer, riparian, sagebrush, and piñon-juniper. The results of the mixed grass prairie experiments showed that this fuel model does not significantly impact archaeological materials located at the soil surface during cool-season prescribed burning. Peak soil surface temperatures during these cool-season burns generally reached 150-300°C and were sustained only briefly for approximately 10-20 seconds. The impact of prescribed burning in grassland fuels on selected experimental artifacts was limited. The most pervasive form of thermal alteration observed during the experiments was combustive residue deposition on the upper surfaces of artifacts. Based on the observations made during this project, combustive residue deposits should not be considered detrimental to the integrity of most archaeological materials. These deposits do weather from artifact surfaces over time depending on environmental and taphonmic conditions. No significant forms of thermal alteration such as thermal fracturing, spalling, or deformation were observed for any artifacts burned during the grassland experiments. The only exception would be light and partial charring of upper bone surfaces in which a portion of the organic component was combusted. The low degree of thermal alteration observed during the grassland experiments is a function of the brief residence times and low maximum soil surface temperatures produced by fine fuels. Subsurface heating during these fires is negligible, even at a depth of only 1cm subsurface. Overall, it is suggested that cool season prescribed burning in mixed grass prairie environments has very limited potential to significantly affect archaeological resources.

In vegetative communities characterized by mixed grass prairie and ponderosa pine, prescribed burning has the potential to significantly impact surface archaeological materials if these materials are in close association with ponderosa logs and litter. During combustion, these fuels can generate soil surface temperatures in excess of 400° for an extended period of time. The heat energy radiated to the soil surface from these fuels is sufficient to thermally alter bone, shell, glass, and some varieties of chert in a significant manner. Where only grassland fuels are present in these environments, the potential for significant impact to archaeological resources is limited due to the incapacity of fine fuels to sustain high levels of radiant heat energy during combustion. The best strategy to mitigate the potential negative impact of prescribed fire on archaeological resources in these environments would be to reduce dead-and-downed ponderosa fuels from know archaeological sites.

Prescribed fires conducted in riparian zones are unlikely to have a significant impact on archaeological materials where fine fuels are dominant. These experiments showed that grasses and small willows produce soil surface heating similar to that observed in mixed grass prairie environments. Thermal alteration of experimental artifacts was limited to combustive residue deposits only. Circumstances in which archaeological materials could be significantly impacted in riparian fuels was only observed in instances where experimental artifacts were placed directly beneath large willow species that were completely combusted during burning. Subsurface heating in riparian zone is mitigated to an even greater extent due to high soil moisture content.

Experiments conducted in sagebrush fuels during prescribed burns show that these fuels can produce soil surface heating in the 300-500°C range. Soil surface heating is generally brief and concentrated directly beneath the canopy of the plant. Significant thermal alteration of experimental artifacts was observed during the experiment, but only for artifacts located immediately beneath sagebrush canopies. Artifacts located outside the periphery of the canopies were minimally impacted. Again, fuel reduction in areas of known archaeological importance would be the most effective strategy in mitigating the effects of prescribed fire in sagebrush communities.

Prescribed fire in mixed conifer environments has the potential to significantly impact archaeological resources particularly in areas were large dead-and-downed ground fuels are present. The experiments conducted in mixed conifer fuels show that logs and large litter can generate soil surface temperatures of over 400° (up to the 600-800°C range in some instances) for extended periods where heavy fuels are present. In instances in which archaeological material, particularly bone and chert were associated with these fuels during combustion, significant forms of thermal alteration such as thermal fracturing, thermal spalling, and partial combustion were observed. Subsurface soil heating beneath a log during the first experiment reached 226.0°C at –2cm, and 105.7°C at –5m. Soil is effective in mitigating the heat pulse radiated by combusting surface fuels and conducted through the soil matrix. It is unlikely that archaeological materials deposited >5cm subsurface would be significantly impacted during prescribed burns in mixed conifer environments (with the exception of instances where root systems are combusted).

Where ground fuels were limited to duff and light vegetation in mixed conifer environments, soil surface temperatures within burn plots peaked rapidly to only 200-300° and were sustained for a short duration. Experimental artifacts in these plots were minimally affected by thermal alteration, generally characterized by heavy combustive residue deposition and light charring. In order to mitigate the impact of prescribed fire on archaeological materials in mixed conifer environments, large ground fuels should be removed or reduced from known archaeological sites.

One prescribed burn experiment was performed in a piñon-juniper vegetative community. The most severe prescribed fire conditions were observed during this experiment. Soil surface temperatures within the burn plot peaked rapidly to temperatures near 800°C where small logs were present. Overall, soil surface temperatures within the plot were sustained at above 400°C for an extended duration. Thermal alteration of experimental artifacts was very pervasive and severe. Unfortunately, only one experiment in piñon-juniper fuels was performed. Additional data would be useful to support the results of the initial experiment. Clearly, however, it is apparent that piñon-juniper fuels have the potential to burn very hot, and the potential for significant thermal alteration of archaeological materials is quite high.

Prescribed burning is an important tool in the management of plant and animal communities. Fire is an important and beneficial component of many ecosystems. The data presented here show that prescribed burning can be conducted with limited impact to archaeological resources in several vegetative communities. However, in environments where heavy ground fuels are present, it is critical that hazardous fuels are removed or reduced in the immediate vicinity of important archaeological sites in order to mitigate the potential for significant thermal alteration of archeological materials. Table 6.1 provides a generalized summary of prescribed burning temperatures and artifact thermal alteration based on fuel type.

Table 6.1: Generalized summary of prescribed burning impact potential.

Fuel Type	Peak Temp (Surface)	Residence Time	Sustained Heating	Fire Impact (Artifacts)
Mixed Grass	100-300°C	10-20 sec	>50°C 3-6 min	Limited
Grass/Mixed Conifer				
(Grass)	100-300°C	10-20 sec	>50°C 2-4 min	Limited
(Grass/Litter)	250-500°C	5-15 min	>200°C 10-20 min	Moderate
(Log)	450-600°C	5-20 min	>450° 10-20 min >200°C 1-2 hrs	Significant
Riparian				
(Grass)	100-200°C	10-20 sec	>50°C 1-3 min	Limited
(Willow Sm.)	100-300°C	1-2 min	>50°C 5-10 min	Limited
(Willow Lg.)	300-500°C	2-8 min	>100°C 5-30 min	Moderate
Sagebrush				
(Small-Med)	150-300°C	1-3 min	>100°C 5-10 min	Moderate
(Large)	250-500°C	2-4 min	>200°C 10-15 min	
Mixed Conifer				
(Duff/Litter)	200-400°C	1-2min	>100°C 3-10 min	Moderate
(Log)	400-800°C	5-20 min	>300°C 20-40 min 100-200°C 2-4hrs+	Significant
Piñon-Juniper				
(Large Litter)	700-800°C	2-4 min	200-400°C 1hr+	Significant

The muffle furnace experiment illustrated the direct relationship between temperature and thermal alteration of specific material types. The experiment was conducted for three purposes: 1) to repeat similar experiments conducted by Bennett and Kunzmann (1985); 2) to establish the extent of thermal alteration affecting a variety of common archaeological material types across differential temperature gradients ranging from 100-1000°C; 3) to provide sets of reference data from which to assess the potential for thermal alteration of archaeological resources given a particular artifact class and maximum temperature range. Summary data from the experiment are provided in Table 6.2.

Table 6.2: Muffle furnace experiment thermal alteration summary.

Artifact	Thermal Alteration	Temperature	Thermal Alteration	Temperature
Hartville Chert	Mineral Oxidation	300-1000°C	Thermal Fracture	500-1000°C
Pecos Chert	Mineral Oxidation	300-1000°C		
Ft. Hood Chert	Mineral Oxidation	200-1000°C	Thermal Fracture	400-1000°C
Bioclastic Chert	Mineral Oxidation	500-1000°C	Thermal Cracking (surface)	400-1000°C
Silicified Wood	Mineral Oxidation	200-1000°C	Thermal Fracture	400-1000°C
Phosphoria	Mineral Oxidation	400-1000°C	Crazing, Thermal Fracture (potlid)	900-1000°C
Porcelinite	Oxidation (black)	900-1000°C		
Obsidian	Fracture Line Enhancement	400-1000°C	Crazing (surface) Vesiculation	600-1000°C 1000°C
Sandstone	Mineral Oxidation	300-1000°C		
Blk/Wht Sherd	Mineral Oxidation	600-1000°C	Paint Oxidation	600-1000°C
Glass	Thermal Cracking Spalling (surface)	200-500°C	Melting Deformation	600-1000°C
Bone	Combustion	100-1000°C	Calcined	700-1000°C
Antler	Combustion	100-1000°C	Calcined	700-1000°C
Teeth	Combustion	100-1000°C	Enamel Fracture Calcined	500-1000°C 700-1000°C
Shell	Combustion	300-1000°C	Delamination	400-1000°C

Overall, the results of the muffle furnace experiment showed that certain artifact classes exhibit consistent types of thermal alteration at specific temperature gradients. For example, several varieties of chert as well as silicified wood exhibit color alterations of increasing prominence beginning at 200-300°C. In addition, some of these lithic materials, particularly Fort Hood chert, Hartville Uplift chert, pink bioclastic chert, and silicified wood, are initially affected by thermal fracturing at temperature of 400-500°C, which increases in severity at higher temperatures. Similarly, the propagation of radial fracture lines within obsidian is initiated at 400-500°C, and consistent fine surface crazing occurs at 600-1000°C, with extreme vesiculation occurring for some varieties at 1000°C. Charred bone (combustion of the organic phase) is characterized by a deep and uniform black or dark brown color, and may be attributed to heating at temperatures between 200-400°C. Calcined bone (thermal alteration of the mineral phase) exhibiting green-gray and blue-gray hues represents heating in the 600-800°C range, and chalky white bone and teeth mixed with very pale brown represents heating in the 900-1000°C. Thermal fracturing and crack propagation of weathered bone may occur at temperatures above 400°C. Black-on-white Ancestral Pueblo pottery sherds are oxidized to pink, reddish yellow, and light red at sustained heating to 800°C, 900°C, and 1000°C respectively. Black mineral paint also becomes faded at these temperatures. Melted glass represents temperatures in the 700-800°C range and above, and thermal fracturing and spalling of glass may occur at temperatures ranging between 200-500°C. Thus, certain types of thermal alteration for a given artifact class may be linked to certain temperature thresholds that may occur during prescribed or wildland fires.

It should be noted, however, that heating artifacts in a muffle furnace is not directly analogous to the type of heating experienced by artifacts under natural fire conditions. Heating in the muffle furnace was generally uniform and protracted compared to the precipitous and severe temperature gradient generated under natural conditions. Nonetheless, the data from the muffle furnace experiment may be used to interpret thermally altered artifacts recovered archaeological contexts, and serve as a rough guide from which to assess the potential impact of prescribed and wildland fire on archaeological resources.

The Intermountain Fire Sciences Laboratory wildland fire simulation experiment was conducted to: 1) Simulate variable fuel loads and wildland fire intensities in a controlled laboratory environment; 2) Incorporate experimental artifacts, representative of a range of artifact classes, into the fire simulations with the purpose of assessing potential thermal alteration given a specific artifact type, fuel load, and fire intensity; 3) Establish the temperature and heat flux ranges at which significant thermal alteration of a specific artifact type occurs; 4) Provide data to make predictions regarding the potential for thermal alteration of archaeological resources under actual field conditions given a specific artifact class, fuel load, and wildland fire burn intensity.

The results of the experiment illustrate that the key variables affecting radiant heat output at the sediment surface are fuel load, wind velocity, and flame angle. Fuel load conditions the amount of available energy for combustion and wind velocity influences the rate of combustion and flame angle. The results of several experimental trials showed that, under several fuel loadings, the high wind velocity treatment pushed flame angles closer to the sediment surface where experimental artifacts were positioned. Increased radiant heat output at the sediment surface directly related to significant thermal alteration of experimental artifacts. Significant thermal alteration of experimental artifacts was observed under the heavy, moderate, and moderate-light fuel loadings under the high wind velocity treatment. Under the lower wind velocity treatment, significant thermal alteration of experimental artifacts was also observed for these fuel loadings, but to a lesser degree. The only experimental trials in which significant thermal alteration of artifacts was not observed were light fuel loadings under both low and high wind velocity treatments.

Thermal alteration of experimental artifacts ranged from combustive residue deposits to extensive thermal fracturing. Table 6.3 summarizes the conditions under which specific artifact types exhibited significant thermal alteration during the experiment.

Table 6.3: Summary of significant thermal alteration (IFSL Lab Experiment)

Artifact	Thermal Alteration	Temperature	Thermal Alteration	Temperature (upper/lower)
Hartville Chert (nodule)	Mineral Oxidation	>400°C	Thermal Fracture	400-550°C up 150°C low
Quartzite (flake)	Mineral Oxidation	>500°C	Thermal Fracture	550-650°C up 250°C low
Pecos Chert (biface)			Thermal Fracture	700-800°C up 250°C low
Obsidian (biface)			Enhanced Fracture Lines	450-800°C up
Bone (mammal)	Combustion	>200°C	Thermal Cracking	>400°C up >100°C low
Antler (elk)	Combustion	>200°C	Thermal Cracking	>400°C up >100°C low
Shell (freshwater)	Combustion	>400°C	Delamination	>400°C up >100°C low
Glass (historic)			Thermal Fracture	400-800°C up 100-300°C low

In general, the results of the experiment show that the Hartville Uplift chert nodule specimens were most susceptible to significant thermal alteration, which consisted of thermal fracturing and color alteration due to mineral oxidation. These forms of thermal alteration were observed where the average peak upper surface temperature was 546.8°C, and average peak lower surface temperature was 189.3°C. However, thermal fracturing of Pecos chert biface specimens was only observed during two high intensity fire simulations where the average peak upper surface temperature for both specimens averaged 816.0°C, and the peak lower surface temperature averaged 293.8°C. Differential rates of thermal fracture between the biface and nodule specimens is likely a function of specimen size and material type thermal properties.

Thermal fracturing and mineral oxidation of Black Hills quartzite flakes was also observed during six experiment trials. Mineral oxidation is associated with an average peak upper surface temperature of 528.8°C. Thermal fracturing was observed where peak upper surface temperatures averaged 565.3°C, and peak lower surface temperatures averaged 277.4°C. Specimen size and quartz particle size are likely important variables affecting thermal alteration of this variety of quartzite. Significant thermal alteration of obsidian specimens was limited to the enhancement of pre-existing radial fracture lines. This was observed during experimental trials in which precipitous and brief heating to above 500°C occurred. Thermal fracturing of obsidian was not observed during the experiment. Conversely, thermal fracturing of bottle glass was observed during ten of the experimental trials. Thermal fracturing was observed where peak upper and lower surface temperatures average 534.2°C and 99.4°C respectively.

Significant thermal alteration of Cliff House Formation sandstone specimens during the IFSL experiment was not observed due to limited residence time of flaming combustion and specimen position on the sediment bed. However, the experiment did show that that the oxidation process (limonite to hematite) is initiated at approximately 300°C. The secondary sandstone thermal alteration experiment (propane torch) confirmed this observation and also established thermal spalling and thermal fracturing thresholds for this type of sandstone. Thermal spalling is initiated at approximately 200-300°C**,** becomes increasingly prominent at 400-500°C, and is pervasive at 500-700°C. Thermal fracturing is initiated at 400-500°C and becomes prominent at 500-700°C.

Significant thermal alteration of pottery sherds was not observed during the IFSL experiment. Thermal alteration was limited to combustive residue deposition ranging from light to very heavy. The results of the secondary thermoluminescence dating experiment show that the TL signals of the sample specimens were not significantly affected by heating during selected fire simulation trials. It is likely that the residence time of flaming combustion during the trials was not sufficient to heat the interior of the sherds to a temperature above 250°C for an extended period. These results do, however, suggest that low to moderate intensity wildland and prescribed fire may not have a significant impact on TL dating of surface pottery sherds.

Overall, the IFSL experiment has demonstrated that significant thermal alteration of a variety of archaeological material types can occur under various wildland fire scenarios. Thermal alteration of archaeological materials is a function of fuel load and wind velocity as it related to fire intensity and flame angle. The results of this research can provide archaeologist with empirical data from which to adequately assess the potential impact of natural fire on archaeological resources given a particular set of variables, and to better interpret thermally altered archeological materials from archaeological contexts.

The field-based research project at Mesa Verde National Park included fire-effects sampling of 72 Pueblo I-III habitation sites that had been burned during various major wildland fires that have occurred at the park. The project was conducted with the purpose of identifying the immediate and long-term implications of wildland fire as it relates to the preservation and interpretation of archaeological materials. Overall, wildland fire at Mesa Verde National Park is a highly significant regional scale site formation process that has immediate and long-term implications for site interpretation and the preservation of archaeological materials ranging in scale from multiple sites to architectural feature to individual artifact.

The results of the project show that oxidation, thermal spalling, thermal fracturing and heat-induced weathered fracturing of architectural elements derived from Cliff House Formation sandstone represented the most pervasive and potentially damaging forms of thermal alteration recorded at the selected sites. These types of thermal alteration have significant implications for the preservation of burned architectural features at Mesa Verde. Oxidation of sandstone was the most common form of thermal alteration recorded during the project. Experimentation has shown that oxidation of Cliff House Formation sandstone is initiated at 200-300°C and becomes more pervasive as thermal spalling and fracturing become prevalent at temperatures ranging between 400-700°C. Thermal spalling and fracturing significantly reduced the pre-fire shape and mass of sampled specimens. Moreover, these forms of thermal alteration lead to increased fragmentation over time as physical and chemical weathering processes act to perpetuate existing thermal fractures.

Surface artifacts sampled during the project were affected less severely than architectural features. Common forms of thermal alteration recorded for artifacts were combustive residue deposits, oxidation/oxidative staining, thermal fracturing, and thermal spalling. Thermal fracturing and spalling can significantly affect the interpretive value of artifact, particularly lithics and black-on-white pottery. Evidence of thermal alteration of artifacts recorded on the surface decreased over time due to weathering, displacement, and erosional processes.

The incidence and severity of thermal alteration of materials at selected archaeological sites is largely a function of fire severity and pre-fire fuel load/fuel type. Sites located in vegetative communities dominated by heavily burned piñon-juniper on canyon slopes and mesa tops exhibited higher incidences of thermal alteration across all material types. Sites located in canyon bottoms were vegetation is comprised of mixed grasses and shrubs were impacted much less severely than those located in piñon-juniper stands. These data suggest that vegetative community and topographic location are important variables in predicting the extent of damage to archaeological sites during wildland fires at Mesa Verde.

In sum, natural fire is a significant regional level site formation process that transforms the archaeological record at various levels ranging from region, to the site, to the level of individual artifact. Schiffer (1987) makes little reference to fire as a site formation process, and where it is addressed, the discussion generally consists of instances in which evidence of fire in the record is the result of human intention. Dialogue about wildland fire is nonexistent in his discussion of regional level environmental site formation processes. Fire is a ubiquitous natural phenomenon affecting the archaeological record to various degrees over large-scale geographical units. Archaeologists should consider the varied and far-reaching implications that natural fire has in transforming the archaeological record, and recognize the potential interpretive and preservation implications of this often overlooked formation process.

Fire-related signatures in the archaeological record do not necessarily portend human intent or human activity. It is important to accurately recognize the effects natural fire has on archaeological materials. For example, is evidence of heavily burned Ancestral Pueblo habitation sites indicative of intentional burning due to warfare or abandonment during prehistory? The data from the Mesa Verde study suggest that this is only one possibility since wildland fires were common in the southwest during prehistory. Does the presence of thermally altered chert artifacts at a site necessarily suggest intentional heat treatment? The data presented in this study show that chert is thermally altered by natural fire to varying degrees depending on temperature. Similarly, is the presence of calcined or heavily burned bone at an archaeological site indicative of campfire cooking or cremation. Again, the answer is no, not necessarily. The results of this study have shown that where heavy fuels are present during natural fire, bone can exhibit significant thermal alteration indicative of high temperatures that could be confused with human activity.

Natural fire does, however, leave some confirmation of its presence in the archaeological record. Artifacts located at the soil surface during natural fire often exhibit a disproportional degree of thermal alteration between upper and lower surfaces in which the greatest degree of thermal alteration is limited to the up surface. In addition, natural fire generally has some effect on most artifact classes such that thermal alteration is not limited to artifacts that are commonly associated with hearths or human fire use. Moreover, natural fire generally affects large-scale geographical units, and consequently has the potential to burn large portions of archaeological sites or multiple sites. Thus, widely dispersed and consistent evidence of burning encountered during survey, site sampling, or larger scale integrative investigation may be useful in differentiating between natural fire or thermal alteration due to human intent. None of the issues presented here are easily addressed; however, the data presented here are the first step in facilitating a better understanding of natural fire in the context of site formation processes.

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