The Effects of Fire and Heat on Obsidian

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Meadow Canyon Prescribed Burn: Effects of Fire on Obsidian Hydration Bands

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Introduction

Upon manufacture, the freshly exposed surface of an obsidian artifact begins absorbing water and a visible hydration band gradually forms. By measuring the width of this band at high magnification, archaeologists can determine how long the obsidian has been absorbing water as well as the relative age of the artifact. Measurements from a large sample of obsidian artifacts and flakes can provide a relative chronology of cultural horizons and under certain conditions direct dates can be obtained (Origer personal communication, 1999). Moreover, Deal (1997:15-17, 1999:2, 14-15), Origer (personal communication, 1999), and Gates (personal communication, 1999) propose that hydration band analysis can provide information about prehistoric fire patterns not possible through tree ring dating or other analytical tools.

Fire affects obsidian by reducing or increasing hydration band width, by diffusing bands so they can no longer be accurately measured, or by eliminating bands entirely, thereby destroying valuable archaeological data. It is therefore easy to understand why scientists are concerned about the potential loss of data during wildfires and prescribed burns.

Forest Service fire management and line officers have argued that since natural wildfires must have taken place repeatedly on archaeological sites in the past, prescribed fires should pose no more threat than natural fires. Yet archaeologists are reluctant to allow prescribed burns on sites with obsidian artifacts until more is understood about the hydration process and its reactions to fire. Furthermore, archaeologists suggest that repeated burning by Native Americans around archaeological sites may have prevented sites from burning prior to white contact, or kept fuel loads low enough to keep wildfires from damaging hydration bands (Anderson 1993:25).

However, most scientists still consider obsidian hydration analysis a reliable and relatively inexpensive dating tool (Ericson 1978; Origer 1996; Deal 1997, 1999). Unless proven otherwise, hydration band analysis must be considered a chronological tool of value to scientists and fire management personnel.

Previous Obsidian Studies

Previous studies have shown that fire affects a variety of archaeological resources (Burgh 1960; Switzer 1974; Pilles 1982, 1984; Lentz 1996; Origer 1996; Trembour 1990; Picha et al. 1991; Rowlett 1991a, 1991b; Wettstaed 1993; Swan and Francis 1988; and Cavaioli n.d). Origer (1996) and (Lentz) 1966 have discussed the effects of fire on obsidian hydration bands. However, relatively few studies have looked at hydration bands both before and after exposure to fires (Linderman 1991; Deal 1997; Green et al. 1998; Benson 1999). Previous studies by Linderman (1991), Deal (1997), and Green et al. (1997) suggest that fuel load, maximum temperature, and duration of heat probably are the major factors involved in damage to obsidian artifacts during fires.

1989 Regional Forester's Challenge Grant Study, Willamette National Forest. In 1989, an experimental prescribed burn was conducted on the McKenzie Ranger District of the Willamette National Forest (Linderman 1991). The burn was designed to refine our understanding of the effects of temperature on obsidian artifacts. Phase I of the study was a prescribed burn in Bunchgrass Meadow, which was selected because of the well documented history of Native American burning in high Cascade meadows. It should be noted that this was a low intensity (light fuel load) prescription burn in a grassland meadow. Before the burn, 20 obsidian artifacts were sent to an obsidian lab, where the hydration bands were measured. After the burn, the bands were once again measured and no detrimental effect was observed.

Phase II involved moderate fuel loads in six slash disposal units. Sixty obsidian specimens with measured hydration rinds were placed in preselected burn plots centered with metal stakes. Temperature sensitive dots and liquid paints with temperature thresholds ranging from 325° to 1400°F were used to determine temperatures. Half the obsidian specimens were placed on the surface; the other half were placed approximately 3.5 cm below surface (duff). Fifty-four of the 60 specimens were retrieved after the burn. Results from this part of the study were dramatically different:

> Of fifty-four flakes that were submitted, only six flakes were not effected [*sic*] by the temperatures of the slash burning.... All of the surface flakes and most subsurface flakes were affected by the temperature generated by the fire; there were no measurable hydration rinds (Linderman 1991:8).

Linderman (1991:8-9) notes that unaffected flakes were in high BTU units, where "flames traveled across the five-meter field test plots in 48-60 seconds, with a flame height of approximately three feet." Linderman (1991:9) was unable to explain why three of the six samples that were treated to temperatures in excess of 1400°F were not affected, and speculates that because they were in high surface BTU units "the heat was enough to alter the subsurface artifact's paint but not of sufficient duration to remove the hydration rind." Linderman recommends further studies to understand these ambiguous results.

Eldorado National Forest Obsidian Hydration Study. Deal (1997, 1999), Eldorado National Forest, conducted obsidian hydration studies before and after two prescribed burns in areas of commercial timber, measuring temperature and duration of heat. The first burn took place in an area that had no history of fire for the past 68 years; the second study took place in an area with a history of repeated prescribed burns.

Although results of thermocouple readings from this study are not yet available, preliminary results from this study indicate that damage to obsidian hydration rinds was significantly greater after the fire in the area with no recent fire history, although damage also occurred in the area with a history of repeated prescribed burns (Deal 1997).

Warner Range Study. Green et al. (1997), Modoc National Forest, studied the effects of a prescribed fire on obsidian hydration rinds. The prescribed fire was ignited in a high altitude sagebrush flat, with varying densities of sagebrush, forbs, and grasses. Tom Origer, Sonoma State University Obsidian Laboratory, measured hydration bands of 90 specimens measured before and after the prescribed burn. The obsidian specimens were treated to three fuel conditions: light, moderate, and heavy.

Temperatures were measured with temperature sensitive tablets, crayons, and paint, which do not yield exact temperatures, but a range. Red tablets melted at 300°F, green at 400°F, yellow at 650°F, and blue at 932°F. Four tablets (red, green, yellow, and blue) were placed under each obsidian specimen. (Green et al. 1997:7-8)

Thirty of the specimens were placed in the low fuel area, where they were originally found. The remaining 60 specimens were placed in areas where the desired fuel loads existed (moderate and heavy fuel areas). (Green et al. 1997:5).

Twenty-five specimens in the light fuel load area were unaffected by the fire and five lost definition of the obsidian rind. Moderate and heavy fuel loads, with higher temperatures, affected a larger number of hydration bands. The number of specimens affected in the high fuel plot was almost identical to that for medium fuels (Green et al. 1997:13-14).

Green concludes that fires in areas of low fuel loadings--where temperature are kept below 400 degrees--will have no significant effect on hydration bands. "Somewhere above 500 degrees and perhaps above 500 or even 550 degrees the hydration rind is affected, causing it to become diffuse and unreadable" Green et al. (1997:14-15). Results from the Meadow Canyon study demonstrate that hydration rinds are damaged at much lower temperatures than suggested by Green's study.

Meadow Canyon Study

In order to restore the health and integrity of plant communities in the Meadow Canyon area of the Toquima Range in central Nevada, the Tonopah Ranger District plans to restore fire as a natural ecosystem recycling process in the sagebrush-grass-forb plant community. However, a dilemma in using prescribed fire as a vegetation management tool emerged in the context of archaeological resources protection. An obsidian hydration study was proposed to determine effects of prescribed fire on the integrity of prehistoric resources in the Meadow Canyon area. Information from this study will help us design ecosystem restoration plans compatible with the protection of our archaeological heritage. (Brack 1996)

Research Design

The purpose of the Meadow Canyon study was to determine the effects of different intensity fires on obsidian hydration bands as well as the effects of fire on chert artifacts. Based on results from previous studies, the Tonopah Ranger District proposed an experiment to study the effects of fire associated with light, moderate, and heavy fuel loads on obsidian hydration bands and determine a relatively "safe" temperature range for obsidian.

The research design called for a large, statistically valid sample with minimal variables. Ninety obsidian specimens were treated to light, moderate, and heavy fuel loads, with two replicate plots for each condition. Ten specimens were set aside for control. All obsidian specimens were placed on the surface. Maximum temperature and duration of exposure were recorded by thermocouples and recorded on data loggers outside the fire line.

Research Hypotheses:

H0: Prescribed fire does not affect obsidian hydration bands, and there is no difference in the effect by fire intensity.

H1: Prescribed fire does affect obsidian hydration bands, and the effect varies by fire intensity.

Because there was insufficient time to gather enough obsidian artifacts and measure their hydration bands before the scheduled burn, 100 obsidian artifacts with hydration bands that had been measured previously at different hydration labs were borrowed from the Modoc National Forest. All specimens were measured after the burn by Tom Origer, Obsidian Laboratory, Sonoma State University.

Since chert is an ubiquitous tool material found at sites in central Nevada, 90 specimens of chert also were included in the experiment. The chert specimens consisted of crude flakes manufactured for the experiment from raw chert collected from a prehistoric chert quarry in the Shoshone Range, about 40 miles west of Meadow Canyon. The flakes varied in size from about 0.5 centimeters to more than 5 centimeters in length. Most of the flakes manufactured for the study were about 1-1.5 centimeter in length. No archaeological artifacts were included. The experiment took place on the morning of September 23, 1997, in Meadow Canyon, Nye County, Nevada.

Research Environment. Meadow Canyon, located on the east slope of Mount Jefferson at an altitude of 8,400 feet, contains large stands of decadent sagebrush, individual plants often reaching more than eight feet high. The study area is a bowl-shaped geological feature approximately 1 x 2 miles in diameter, cut by a vigorous perennial stream. Bordering the stream are low ridges containing moderately dense lithic scatters of chert and obsidian tools and waste flakes, and groundstone. Nearly every ridgeline contains a site. Presence of groundstone indicates that the Native Americans who populated this region prior to the arrival of Europeans processed grasses, roots, and/or medicinal plants at these locations.

Native American Burning Practices. Ethnographers Julian Steward and Omer Stewart both refer to the burning practices of the Paiute and Shoshone peoples who occupy the Great Basin.

> The brush in "basins" in the hills near the winter [Paiute] villages was burned and *Mentzelia* and *Chenopodium* seeds were broadcast. There is no question that this practice was native, for it was described *in all parts of north central Nevada* [emphasis mine]. (Steward 1938:104).

Stewart repeatedly commented on Native American burning practices specific to central Nevada, as well as the Great Basin as a whole. Fire as a land management tool clearly has a long history in the Great Basin and in Meadow Canyon specifically.

With the arrival of white settlers and mineral prospectors in the 1860s, and subsequent large scale mining, the Western Shoshone were left with little choice but to adopt wage labor as their primarily mode of subsistence, and to a large extent abandoned traditional practices of gathering native plants. Change in subsistence modes and, finally, fire abatement practices established by government agencies effectively stopped widespread burning of native plants and grasses. This is the probable scenario for what happened in Meadow Canyon. The Tonopah District hopes to reintroduce fire into the ecosystem and bring back native grasses.

The Meadow Canyon Prescribed Burn. September 22, 1997, the day before the burn, nine subplots were selected in a rectangular area 132 x 174 feet (about 0.53 acre). Three test plots with sparse ground cover of forbs, grasses, and light sagebrush were designated for light fuel loads, three with forbs, grasses and moderately dense sagebrush were designated for moderate fuel loads, and three with very dense sagebrush were designated for heavy fuel loads. Fuel and soil moisture content were measured prior to ignition.

Stephen Sackett, Sally Haase, and Gloria Burke, scientists from the Pacific Southwest Research Station in Riverside, California, positioned thermocouples in the test plot to provide accurate measurements of maximum temperatures and duration of heat. Once the thermocouples were in place, 90 obsidian artifacts and 90 chert flakes were distributed equally among the nine test plots. Two pieces of chert and two pieces of obsidian were placed as close as possible (about 1-2 centimeters) to each thermocouple. All specimens were placed on the ground surface; however, some thermocouple readings were taken below surface.

The morning of September 23, 1997, the fire crew ignited the burn on the upslope side of the test plot. Fifteen-foot flames quickly shot up and the fire rapidly spread across the test. The fire was over within 10 minutes. (Sackett and Haase 1998). The following morning, 89 of the 90 obsidian specimens were recovered. All of the chert flakes were severely damaged and many had shattered beyond recognition. Total recovery of the chert was therefore impossible. The 89 recovered obsidian specimens were sent along with the control specimens to the Obsidian Laboratory, Sonoma State University, where the hydration bands were measured by Tom Origer.

Results

Table 1 shows maximum temperature and change in hydration rind thickness. Table 2 contains data for the 10 control specimens. Table 3 lists maximum temperature and duration of time exposed to temperatures above 80, 100, and 140°F. Table 4 shows temperatures below and above 500°F as related to unaffected and affected hydration data. Although the flames died down after only 10 minutes, temperatures above 140°F persisted over 12 hours after ignition at one location.

Heavy Fuel Subplots. Only one specimen in heavy fuel subplots (No. 1370-20a) was not affected. Although the hydration band of this specimen was diffuse, Origer was able to measure the hydration band thickness at 4.0 microns, a change of only 0.2 microns. The (subsurface) thermocouple probe recorded a maximum temperature of 96°F; no surface temperature was recorded for this specimen.

Hydration bands of all other specimens were either diffuse or not visible after the fire. Maximum surface temperatures ranged from 169 to 1324°F. A combination of high temperatures, long exposure durations (5.6 to 25.7 hours), and heavy fuel loads proved detrimental to obsidian hydration rinds, fully supporting the hypothesis (H1). (Table 1, page 3 and Table 3, page 3)

Moderate Fuel Subplots. Results in moderate fuel subplots were slightly different. Only three specimens were unaffected. Two of these were exposed to a maximum temperature of 183°F and one specimen to 1033°F. Surface temperatures of affected specimens ranged from 177°F to 1033°F. (Table 3, page 2)

Fifteen specimens exposed to temperatures below 500°F were affected; nine specimens treated to higher temperatures (above 500°F) were affected (Table 4). Specimen No. 1307-1b was exposed to a high temperatures of 1033°F, but to temperatures above 100°F for only 1.0 hour (Table 3, page 2). As in Linderman's study, duration of exposure may explain why this hydration band was not affected. Note that the Meadow Canyon results refute Green's (1997) statement that temperatures under 400°F probably do not damage hydration rinds. Temperatures at which damage occurred were much lower in the Meadow Canyon study.

Overall, duration of exposure was a factor, particularly when compared with specimens from light fuel and heavy fuel plots; yet some results are puzzling. Why, for example were hydration bands of two specimens affected when treated to maximum temperatures of only 165°F and temperatures over 100°F for less than 0.4 hour?

Light Fuel Subplots. Hydration bands on 12 specimens in low fuel plots were not affected, while 16 were affected. The band of one specimen that was reported as diffuse before the fire was measurable after the fire.[1] Thermocouple readings are not available for this anomalous specimen. Surface temperatures in low fuel plots ranged from 98°F to 820°F, lower overall than temperatures in moderate and heavy fuel plots.

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[1]This anomalous result may be due to different lab technicians before and after the fire.

Several results are quite surprising. Five of 12 hydration bands not affected were exposed to maximum temperatures of 530°F and higher, while only four of the affected specimens were treated to 530°F or higher. Furthermore, eight affected hydration bands were exposed to low temperatures ranging from 98 to 499°F (See Table 4). Duration of exposure was not always a factor, as evidenced by specimen Nos. 407-1511f and 407-1621b, which were treated to a relatively high temperature of 549°F and to temperatures above 100°F for 6.0 hours (Table 3, page 1). Looking at the same table, the above may be contrasted with those for specimen No. 407-1499q, exposed to 161°F and above 100°F for only 1.3 hours.

Chert Results. All chert specimens in this study were severely damaged; those that survived were covered with a thick coat of soot. Many pieces shattered into so many fragments, it was impossible to collect all the pieces. 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. Although analysis of the chert specimens was limited to visual observation, this study demonstrates that fire is highly detrimental to chert artifacts. Since 90% of tool stone on the Tonopah Ranger District is chert, sites should be protected from all fires. It would be interesting to know whether heat-treated chert artifacts withstand the effects of fire better than the raw chert used in this study.

Control Sample. Hydration band measurements for the ten control specimens also changed (Table 2), but all were measurable. Three measurements deviated from the original reading by 0.2 microns or less, which is not significant. Technicians normally take six separate measurements of each sample, using the mean of all six measurements. Typically, individual measurements by the same technician often fluctuate as much as 0.2 microns. Measurements taken by different technicians also deviate, and some technicians tend to obtain consistently higher or lower measurements than the mean (Stevenson, Dinsmore, and Scheetz 1989), which may in part explain the deviations observed within the control samples. Further comments are reserved until further study.

Summary of Results

Results from the Meadow Canyon study confirm that fire affects obsidian hydration bands and that there is a direct relationship between fuel load (and temperature) and effect. Obsidian samples in heavy and moderate fuel plots were more likely to be affected than those treated to light fuel loads, confirming the H1 hypothesis. The null hypothesis (H0) was rejected.

We also learned that some obsidian specimens treated to high temperatures are not affected. Overall, more affected specimens were treated to temperatures below 500°F than above, which was not expected.

This study suggests that a more realistic "safe temperature range" probably falls between 250-300°F, or lower. At present, fire management manuals place this safe range at 500°F. Clearly, the safe temperature range should be lowered. A few hydration bands will be damaged regardless of temperature and a few will be unaffected by extremely high temperatures.

Implications and Recommendations

Although test results demonstrated that heavier fuel loads are more detrimental to obsidian hydration bands, the present study showed that most hydration bands treated to temperatures above 300°F will be affected. This is significantly lower than the temperatures currently recommended in fire management handbooks.

Until we have a better understanding of the effects of fire on hydration bands, we should try to prescribe burns below 300°F when obsidian is present. Even this will not guarantee protection of all obsidian hydration bands. Archaeologists and fire management personnel should take active steps to protect sites

before prescribed fires. Sagebrush and other undergrowth can be cut and removed from sites before the burn. One National Park Service archaeologist provides his survey crew with pruning shears. Exposed obsidian artifacts and flakes identified prior to a fire can be removed or buried, and locations mapped and recorded. With low fuel loads, depths of 3-4 centimeter probably are acceptable, but higher temperatures will require greater depths.

Further research may explain why so many artifacts exposed to low temperatures were damaged during the Meadow Canyon fire and, conversely, why some hydration bands endured high temperatures.

Future temperature related studies should probably take place in the lab. Origer (see Loyd, this volume) and Sackett both have proposed heating obsidian samples in ovens, where temperatures can be controlled. This procedure is also much less expensive than a prescribed burn. In the lab it should be possible to concentrate on temperature without other factors interfering, but length of exposure should also be tested. It should be possible to determine what combinations of temperature and exposure time will avoid damaging obsidian rinds.

In the Meadow Canyon study, different obsidian lab technicians measured hydration bands on many of the specimens before and after the prescribed burn. Ideally, all specimens should be measured by the same technician before and after the fire. This does not appear to be a major problem in the present study, since most of the hydration bands disappeared or were diffused; however, it could be a problem in future studies, especially with low fuels.

Based on the results of the Meadow Canyon study, another study is recommended to validate or reject the results. As in the Meadow Canyon study, a large sample is recommended, but the study should concentrate on obsidian exposed to low temperatures and light fuel loads. Hydration rinds should be measured before and after the prescribed fire by the same lab technician. Obsidian sources also should be taken into consideration in order to determine whether obsidian from certain sources withstands higher temperatures than obsidian from other sources. Some samples should be placed under the ground surface in an attempt to determine depth at which obsidian is no longer affected.

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Stephen S. Sackett, Sally M. Haase, and Gloria Burke set up the thermocouples in the field and prepared the final report on temperatures and duration of exposure. I am particularly grateful for their expertise.

Tom Origer, Director, Sonoma State University Obsidian Laboratory, measured the hydration rind thickness of the obsidian specimens after the burn. Origer was also an indispensable source of information and advice.

Austin Ranger District Archaeologist Christi Shaw assisted with the project design, preliminary data recording, photography, and field setup. Shaw also helped manufacture the chert flakes used in the study.

Fire Management Officer Dave Haney and his crew prepared the burn plot and implemented the burn with the assistance of Mike Dondero, Fire Management Officer from the Carson Ranger District. I was impressed with the skill of the fire crew in managing the burn.

Modoc National Forest Archaeologist Gerald Gates loaned the obsidian artifacts used in the study. Hydration rinds on all of the loaned artifacts had already been measured, making it financially feasible to study a large, statistically valid sample of obsidian specimens on short notice.

Jeanne Chambers and Robin Tausch, USFS research scientists stationed at the University of Nevada, Reno, provided background information on the history of fire in central Nevada and other pertinent data.

A number of archaeologists were generous with their time and records. Inyo N.F. Archaeologist Linda Reynolds allowed me access to her library and gave permission to photocopy several papers. Eric Berglund, Region 6 Zone Archaeologist, provided me with a copy of the McKenzie study, and Coconino N.F. Archaeologist Peter Pilles provided valuable information.

Librarians and graduate students at the University of Nevada, Reno campus helped locate government publications with pertinent data. Diane Hartsock, Tonopah Public Library, obtained copies of many referenced publications.

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Table 1. Maximum Temperatures and Hydration Band Measurements Before and After Prescribed Fire.

LOW FUEL LOAD

	Before (mμ)	After (mμ)	Difference (mμ)	Maximum Temperatures Surface (°F)	Below Surface (°F)
Unaffected					
1390-12	4.0	3.6	-0.4	531	80
1390-32	5.7	5.8	+0.1	787	
1166-10b	5.2	7.2	+2.0		86
407-1618w	3.3	3.5	+0.2	530	130
407-1511f	3.7	3.2	-0.5	549	
407-1621b	1.8	1.5	-0.3	549	
407-1499y	4.3	~3.0	-1.3	161	
407-1679j	3.6	3.5	-0.1	98	108
407-1680i	3.1	3.0	-0.1	259	
407-1671f	3.0	~3.0	0.0	227	
407-1499h	1.8	1.2	-0.6	*	
407-1499w	3.7	DH (~4.0)	+0.3	322	
Affected					
1390-35	4.2	DH	NA	531	80
1342-2a	4.3	DH	NA	787	
1369-3b	3.8	DH	NA		86
1369-11a	3.2	DH	NA	379	
1166-6a	4.0	DH	NA	379	
1342-21a	3.2	DH	NA	499	
1369-7a	3.6	DH	NA	499	
407-1499ee	1.8	DH	NA	530	130
407-1618aa	3.6	DH	NA	322	
407-1499q	3.2	NVB	NA	161	
407-1706d	2.7	DH	NA	98	108
407-1697i	3.2	DH	NA	820	
407-1678h	3.5	NVB	NA	820	
407-1681l	3.2	DH	NA		141
407-1684f	NVB	DH	NA		141
1339-51b	3.8	*			
407-1682c	1.3	NVB	NA	227	
Anomalous Result					
407-1618v**	DH	3.7	NA	*	

* No data.

** Diffused band before fire; visible band after fire.

Table 1 (continued). Maximum temperatures and Hydration Band Measurements Before and After Prescribed Fire.

MODERATE FUEL LOAD

	Before (mμ)	After (mμ)	Difference (mμ)	Maximum Temperatures Surface (°F)	Below Surface (°F)
Unaffected					
1337-55b	4.5	3.5	-1.0	183	
1339-25a	3.6	DH (ca.3.5)	-0.1	183	
1307-1b	5.7	DH (ca.3.5)	-0.2	1033	
Affected					
1339-51a	4.3	NVB	NA	466	96
1339-55d	4.4	NVB	NA	307	
1307-6a	5.2	DH	NA	466	96
1344-68c	5.2	DH	NA	307	
1339-22a	48	DH	NA	1033	
1307-20a	4.4	DH	NA		98
407-1678a	2.6	DH	NA		98
1339-9b	4.9	NVB	NA	463	83
1260-3	1.6	NVB	NA	463	83
1260-5	1.5	NVB	NA	165	
1260-4a	3.0	DH	NA	165	
1337-53a	1.7	NVB	NA	373	
1336-58a	5.7	DH	NA	373	
1336-12b	4.3	DH	NA	572	
1260-12	2.7	DH	NA	572	
1336-48a	5.2	DH	NA	551	
1337-98a	1.8	NVB	NA	551	
407-1702b	2.6 + 3.8*	DH	NA	338	92
407-1702g	3.4	DH	NA	338	92
407-1699a	1.6	DH	NA	531	
407-1713a	1.6	DH	NA	531	
407-1709d	3.2	DH	NA	409	
407-1713h	2.9	DH	NA	409	
1336-12a	4.1	DH	NA	952	
407-1710i	2.0	DH	NA	952	
407-1711j	2.9	DH	NA	177	
407-1709b	4.8	NVB	NA	177	

* Two bands.

Table 1 (continued). Maximum Temperatures and Hydration Band Measurements Before and After Prescribed Fire.

HEAVY FUEL LOAD

	Before (mμ)	After (mμ)	Difference (mμ)	Maximum Temperatures Surface (°F)	Below Surface (°F)
Unaffected					
1370-20a	3.8	DH (c.4.0)	+.02		96
Affected					
407-1675a	2.1	NVB	NA	672	125
407-1684e	4.0	NVB	NA	672	125
407-1709k	4.1	DH	NA	424	
407-1684i	2.7	NVB	NA	424	
407-1684a	3.6	NVB	NA	815	
407-1684m	3.0	NVB	NA	815	
407-1723b	2.1	DH	NA	1324	
407-1676b	3.7	DH	NA	1324	
407-1719k	4.4	DH	NA	169	
1370-43b	4.3	DH	NA	596	102
1370-58a	3.6	DH	NA	596	102
1370-92a	4.3	DH	NA	799	
1370-57b	2.5	DH	NA	799	
1370-18b	3.8	DH	NA		96
1370-60c	1.5	DH	NA	501	
1370-55a	3.0	DH	NA	501	
1370-55c	3.1	DH	NA		546
1370-57a	3.4	NVB	NA		546
1344-68a	5.5	DH	NA	802	136
1344-81a	4.4	DH	NA	802	136
1370-18a	3.7	DH	NA		142
1344-7c	4.9	NVB	NA		142
1370-8a	3.7	NVB	NA	373	
1344-30a	5.4	NVB	NA	373	
1370-55b	1.6	NVB	NA	647	
1344-68b	4.7	NVB	NA	647	
1370-57c	3.6	NVB	NA	697	
1344-26a	4.5	NVB	NA	697	

Table 2. Control Sample Results.

	Before (mμ)	After (mμ)	Difference (mμ)
Control			
1344-3a	5.7	6.2	+0.5
1344-3b	5.8	5.7	-0.1
1344-7a	3.4	2.9	-0.5
1344-7b	3.6	3.2	-0.4
1344-26d	7.5	7.2	-0.3
1344-43a	4.3	DH (−4.4)	+0.1
1344-43c	4.0	3.4	-0.6
1344-81c	4.2	3.2	-1.0
1307-2b	5.0	3.4	-1.6
1307-3a	2.4	1.4	-1.0

Table 3. Temperature and Duration of Exposure

LOW FUEL LOADS

FSMA No.	Temperature (°F) Surface	Temperature (°F) Below Surface	>80°F (hours)	>100°F (hours)	>140°F (hours)
Unaffected					
1390-12	531		4.2	1.8	0.6
"		80	0.1	0.0	0.0
1390-32	787		7.8	2.0	1.1
1166-10b	4.0	86	1.1	0.0	0.0
407-1618w	530		9.8	4.1	2.7
"		130	8.4	4.2	0.0
407-1511f	549		11.0	6.0	1.3
407-1621b	549		11.0	6.0	1.3
407-1499y	161		8.2	1.3	0.3
407-1679j	98		2.3	0.0	0.0
407-1680i	259		9.9	3.3	0.2
407-1671f	227		4.4	1.2	0.6
407-1499h	*				
407-1499w	322		10.1	4.0	0.7
Affected (DH/NVB)					
1390-35	531		4.2	1.8	0.6
"		80	0.1	0.0	0.0
1342-2a	787		7.8	2.0	1.1
1369-3b		86	1.1	0.0	0.0
1369-11a	379		6.9	2.4	0.9
1166-6a	379		6.9	2.4	0.9
1342-21a	499		7.3	2.5	1.0
1369-7a	499		7.3	2.5	1.0
407-1499ee	530		9.8	4.1	2.7
"		130	84	4.2	0.0
407-1618aa	322		10.1	4.0	0.7
407-1499q	161		8.2	1.3	0.3
407-1706d	98**		2.3	0.0	0.0
"		108**	4.3	0.6	0.0
407-1697i	820		9.2	4.3	1.6
407-1684f		141	2.9	1.0	0.0
407-1678h	820		9.2	4.3	1.6
407-1681l		141	2.9	1.0	0.0
1339-51b	259		9.9	3.3	0.2
407-1682c	227		4.4	1.2	0.6
Anomalous Result					
407-1618v***	*		*	*	*

* No data.

** Below ground temperature higher than surface temperature.

*** Diffuse band before fire; visible band after fire.

Table 3 (continued). Temperature and Duration of Exposure.

MODERATE FUEL LOADS

FSMA No.	Temperature (°F) Surface	Below Surface	>80°F (hours)	>100°F (hours)	>140°F (hours)
Unaffected					
1337-55b	183		3.9	1.0	0.3
1339-25a	183		3.9	1.0	0.3
1307-1b	1033		7.8	1.0	0.6
Affected (DH/NVB)					
1307-6a	466		13.4	7.9	5.6
"		96	4.0	0.0	0.0
1399-51a	466		13.4	7.9	5.6
"		96	4.0	0.0	0.0
1337-55d	307		8.6	4.3	2.7
1344-68c	307		8.6	4.3	2.7
1339-22a	1033		7.8	1.0	0.6
1307-20a		98	1.0	0.0	0.0
407-1678a		98	1.0	0.0	0.0
1399-9b	463		7.3	1.8	0.8
"		83	0.8	0.0	0.0
1260-3	463		7.3	1.8	0.8
"		83	0.8	0.0	0.0
1260-5	165		1.3	0.4	0.0
1260-4a	165		1.3	0.4	0.0
1337-53a	373		7.5	2.0	1.1
1336-58a	373		7.5	2.0	1.1
1336-12b	572		8.3	2.0	0.9
2160-12	572		8.3	2.0	0.9
1336-48a	551		4.0	1.6	0.5
1337-98a	551		4.0	1.6	0.5
407-1702b	338		8.4	3.9	2.5
"		92	3.3	0.0	0.0
407-1702g	338		8.4	3.9	2.5
"		92	3.3	0.0	0.0
407-1699a	531		17.1	8.3	3.6
407-1713a	531		17.1	8.3	3.6
407-1709-d	409		8.4	4.1	2.8
407-1713h	409		8.4	4.1	2.8
1336-12a	952		15.6	8.3	4.1
407-1710i	952		15.6	8.3	4.1
407-1711j	177		3.4	0.8	0.2
407-1709b	177		3.4	0.8	0.2

Table 3 (continued). Temperature and Duration of Exposure.

HEAVY FUEL LOADS

FSMA No.	Temperature (°F) Surface	Below Surface	>80°F (hours)	>100°F (hours)	>140°F (hours)
Unaffected					
1370-20a		96	1.6	0.0	0.0
Affected (DH/NVB)					
407-1675a	672		11.3	6.9	4.1
"		125	10.1	3.7	0.0
407-1684e	672		11.3	6.9	4.1
"		125	10.1	3.7	0.0
407-1709k	424		16.4	13.3	8.1
407-1684i	424		16.4	13.3	8.1
407-1684a	815		14.3	7.6	4.4
407-1684m	815		14.3	7.6	4.4
407-1723b	1324		11.9	7.1	3.8
407-1676b	1324		11.9	7.1	3.8
407-1719k	169		5.6	2.6	0.7
1370-43b	596		12.3	6.3	4.8
"		102	8.8	0.8	0.0
1370-58a	596		12.3	6.3	4.8
"		102	8.8	0.8	0.0
1370-92a	799		12.7	9.6	9.4
1370-57b	799		12.7	9.6	9.4
1370-18b		96	1.6	0.0	0.0
1370-60c	501		14.3	8.3	2.5
1370-55a	501		14.3	8.3	2.5
1370-55c		546	17.5	7.6	3.8
1370-57a		546	17.5	7.6	3.8
1344-68a	802		14.4	9.9	7.1
"		136	14.9	8.0	0.0
1344-81a	802		14.4	9.9	7.1
"		136	14.9	8.0	0.0
1370-18a		142	10.9	5.3	0.4
1344-7c		142	10.9	5.3	0.4
1370-8a	373		9.6	4.7	2.6
1344-30a	373		9.6	4.7	2.6
1370-55b	647		21.0	12.9	9.4
1344-68b	647		21.0	12.9	9.4
1370-57c	697		25.7	16.4	12.4
1344-26a	697		25.7	16.4	12.4

Table 4. Temperatures Above and Below 500° F.

(Note: Only surface temperatures included.)

	Light Fuel (° F)	Moderate Fuel (° F)	Heavy Fuel (° F)
UNAFFACTED SPECIMENS (Measurable hydration band)	98	183	none
	161	183	
	227	1033	
	259		
	322		
	*		
	530		
	531		
	549		
	549		
	787		
AFFECTED SPECIMENS (No visible band or diffused band)	98	177	169
	161	177	373
	227	165	373
	322	165	424
	379	307	424
	379	307	501
	499	338	501
	499	338	596
	530	373	596
	531	373	647
	787	409	647
	820	409	672
	820	424	672
		424	697
		466	697
		466	799
		501	799
		531	802
		551	802
		551	815
		572	815
		572	1324
		952	1324
		952	
		1033	

* No data