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Nondestructive Monitoring of Wooden Native American Pyramidal Structures

Michael Joseph Shoriak

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Nondestructive Monitoring of Wooden Native American Pyramidal Structures

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NONDESTRUCTIVE MONITORING OF WOODEN NATIVE AMERICAN PYRAMIDAL STRUCTURES

Michael Joseph Shoriak

A THESIS

in

Historic Preservation

Presented to the Faculties of the University of Pennsylvania in Partial Fulfillment of the Requirements of the Degree of

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2012

Advisor
Michael C. Henry, PE, AIA
Adjunct Professor of Architecture

Program Chair
Randall F. Mason, Ph.D.
Associate Professor of City and Regional Planning
To Wood
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Introduction

This thesis addresses the need for a non-contact, non-destructive methodology for monitoring changes in configuration and material condition of wooden structures constructed in Grand Canyon National Park by the Navajo and Havasupai Native American Tribes. Beginning in the late 19th century, Navajo and Havasupai family groups lived in seasonal community camps along the south rim of the Grand Canyon. During the 1950s, the National Park Service relocated both tribes from the Grand Canyon National Park leaving behind many different types of abandoned Native American wooden structures in settlement camps throughout the Park landscape. As part of this thesis, two methods have been investigated and developed for monitoring the structural engagement and fixity and condition of these structures. First, a photographic survey method is described that provides a technique to detect changes in the engagement and fixity of the wooden structural forked pole primary members. Second, Infrared Thermography is evaluated as a potential method to detect core deterioration in the wood forked pole primary members. This thesis presents the trial results of the proposed methods using models and sample materials under controlled interior conditions. The results indicate that the two methods are feasible; however, field conditions can be highly variable with respect to several critical of factors. The results of infrared thermography are affected by changes in environmental and material factors such as solar radiation, moisture content of the wooden members, temperature, relative humidity, weather conditions and wood species. This thesis concludes by setting out a recommended program for future field testing.
The National Park Service is responsible for the documentation and preservation of wooden Native American structures in Grand Canyon National Park and the Navajo and Havasupai Tribes have input on the management of these resources. Hundreds of community camps have been identified by the National Park Service and they have engaged the University of Pennsylvania Architectural Conservation Laboratory to develop a monitoring plan for these structures consistent with the limitations of Native American consultation requests. NPS consultation with tribal affiliates resulted in the request that these structures not be subjected to any physical repair or stabilization interventions and remain unaltered. This constrains not only conventional methods for preserving wood structures, but also the methods available for assessing the weathering and rate of deterioration as well as any visible change of these structures over time.

Pyramidal forked pole wooden Native American structures are the focus of this thesis including hogans, wikiups and sweatlodges. Pyramidal hogans, wikiups and sweatlodges are constructed using 3 or 4 wooden forked pole primary structural members that are buried in the ground and the opposite forked ends are interlocked forming a pyramid. Secondary wooden members were laid on the primary structural members serving as cladding. Sweatlodges, constructed by both tribes, are smaller versions of hogans and wikiups used for ceremonial purposes. All three types of Native American structures were originally covered in soil and tree bark; later mid-20th century structures incorporated sheet metal roofing panels and steel wire in place of traditional organic materials. Today only the primary and secondary wooden members and some modern inorganic materials, such
as corrugated sheet metal roofing panels and tie wire remain on some structures. The high frequency of the documented collapse of pyramidal forked pole Native American structures by the Park Service is evidence these structures are at higher risk of deterioration related loss than other more stable Navajo and Havasupai structures. As a result, this thesis develops two separate methods to detect changes in the structural engagement and fixity and condition of wooden pyramidal forked pole structures over time.

Changes in the fixity and engagement of the primary members of pyramidal forked pole structures are the first indication of structures at risk of collapse. In pyramidal structures with four forked pole primary structural members, there are 6 to 8 points of fixity depending on the engagement at the apex, 4 of which are at the base of the structures. Movement of the apex of pyramidal wooden structures is an indication of potential structural instability due to loss of engagement of the primary members; often this is the result of the deterioration of the primary structural members or other external environmental forces. As the apex shifts laterally, loss of engagement, and therefore loss of fixity progresses; ultimately full disengagement of one or more members occurs, leading to instability of the structure under its own weight or external loads. Documented changes in the position of the primary members in relation to each other either by displacement of the primary members or shifting of the contact point between the primary members due to deterioration are relative indications of the progress of a structure from a stable state to an unstable state. A survey method for the detection of displacement of the primary members over time is outlined in Chapter 5: Monitoring Visual Change in the
Engagement and Fixity of Structural Members. This method is capable of producing the necessary repeatable and comparable documentation for each of the structures for monitoring the relative position of the primary structural members of a particular structure over time. The survey method provides information about the movement of forked pole primary structural members at an appropriate resolution and accuracy to successfully identify only those structures at risk of collapse while respecting Native American requests.

The second monitoring method for wooden pyramidal structures considers Infrared Thermography to identify the loss of the core material of wooden forked pole primary structural members. Based on the findings of a literature review of published material describing the physical properties of wood species used in the construction of Native American wooden structures located in Grand Canyon National Park, the wood species used by the Navajo and Havasupai for primary structural members deteriorates in a predictable pattern, leaving, at advanced stages of deterioration, a hollow wood cylinder. Therefore, a nondestructive testing technique is needed that has the ability to identify advanced deterioration of core materials in the forked pole primary structural members. This thesis demonstrates that the proposed monitoring method can reliably identify core loss in proxy primary structural members in a controlled environment; the detection threshold for such losses is low enough to monitor core material before the loss is sufficient for member failure.
The proposed condition assessment method using Infrared Thermography does not require any destructive testing or contact with the structure. This thesis demonstrates that the resolution and portability of commercially available, moderately priced infrared cameras make Infrared Thermography a viable nondestructive method for identifying deterioration of wooden members in a controlled setting. Chapter 11: Results of Laboratory testing describes the results of laboratory testing using Infrared Thermography.

This thesis includes the design, testing and evaluation of the effectiveness of the proposed method for monitoring changes in the structural engagement and fixity of wooden Native American structures and a separate method to determine the material condition of forked pole primary structural wooden members used in the construction of these structures. In each case, testing was based on a lab protocol using proxies to mimic the conditions in the field to determine if each method is feasible for use in Grand Canyon National Park. Both methods respect restrictions imposed by Native American consultation.

Following a description and analysis of the two proposed monitoring methods, the Conclusions and Recommendations chapters summarize the results of lab testing and provide recommendations for adapting the lab methodology used in this thesis to a program for field monitoring. Suggestions for future testing are also provided to further refine and improve the methods developed in this thesis.
Chapter 2: Use and Stewardship of Native American Pyramidal Structures in Grand Canyon National Park

Beginning in the late 19th century, both Navajo and Havasupai family groups migrated from spring and summer seasonal camps inside the Grand Canyon to fall and winter seasonal camps on the south rim of the Canyon. They would often return to the same camps and structures each year to hunt, collect pinyon nuts, graze their livestock and harvest summer crops. Following the designation of Grand Canyon National Park by the United States Government in 1919, Havasupai and Navajos employed by the Park continued to live in the pinyon-juniper woodland on the south rim of the canyon, however, the tribes access to spring and summer sites inside the canyon was restricted. Indian Gardens Campsite, located on Bright Angel Trail, derives its name from the Havasupai camps located at the current campsite area. Havasupai and Navajo family groups continued to live in these camps in Grand Canyon National Park until the 1950s, when all Native Americans were actively removed by the Park service. Jeremy Haines describes the removal of Native American peoples from Grand Canyon National Park. He states:

“In 1956, the Park Service physically removed all the unemployed Havasupai’s living at Supi camp, and destroyed many contemporary and historic Havasupai structures throughout the Park. A February 1956 NPS report mentions the burning of a number of old Indian hogans in the Grandview area that had been “littering the park for years” (NPS 1956 sourced in Wray 1990:91). An informant told Wray (1990) that in 1951 or 1952 the Park Service burnt down numerous structures including Big Jim’s home at Pasture Wash (93).”

Beginning in the 1980s the Park Service has transformed its view of the historic nature of wooden Native American structures located in the Park and today the National Park Service is actively documenting and protecting wooden Native

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American sites. Recent efforts in 2006 by Grand Canyon National Park have focused on developing a documentation and monitoring plan for historic Native American wooden structures located in the Park.

Today there are 165 identified sites and possibly hundreds more still unidentified in the pinyon-juniper woodlands on the south rim of the Park. The National Park Service has determined that the identified structures were constructed between 1890-1955 based on metal cans and other household containers left around the sites. According to Park Service staff, approximately 2 of these structures are lost each year due to vandalism or deterioration related collapse. This has provided a sense of urgency to the effort to document and preserve the remaining structures.

In “Architectural Documentation and Preservation of Havasupai and Navajo Wooden Pole Structures in Grand Canyon National Park”, Ian Hough and Ellen Brennan describe the first attempt by the National Park Service to gather information about the history and construction of wooden pole structures built by the Havasupai and Navajo Native American Tribes in Grand Canyon National Park. As part of the documentation effort, Grand Canyon National Park consulted both the Havasupai and Navajo Tribes concerning the preservation of these structures. Both Tribes have responded that they do not want invasive or destructive study carried out on pyramidal wooden pole structures and Navajos believe that

2 Haines, Ethnicity and Historic Native American Architecture, 21
4 Ian Hough and Ellen Brennan, “Architectural Documentation”, 81
they should be allowed to deteriorate naturally. In particular, the Navajo Nation Historic Preservation Department singled out sweatlodges as a building type to be left without intervention.5 Although both the Havasupai and Navajo Tribes ask that these structures not be altered, they have requested that Native American specialists brace at risk structures.

Following Native American consultation, Grand Canyon National Park decided to preserve these structures using “methods of architectural preservation includ[ing] architectural documentation, stabilization, cyclic monitoring, and law enforcement protection.”6 In 2006, the Park Service selected 10 structures, 3 forked pole wickiups or hogans and 7 sweat lodges, for documentation based on their high material and formal integrity. The National Park Service hired Western Mapping to scan the pole structures using Light Detection and Ranging (LIDAR) remote sensing technology to provide detailed documentation of the form and condition of these structures in 2006. Following documentation by laser scanning, the Park Service engaged the University of Pennsylvania Architectural Conservation Laboratory to develop methods that can monitor deterioration rates and identify specific threats to the Native American wooden structures located in Grand Canyon National Park.

Treatments will be developed for wood pyramidal structures determined to be at risk of collapse in accordance with Native American consultation requests. In the event of the identification of a site that is in danger of collapse or the “architectural remains experience a rapid rate of deterioration due to natural or

5 Marklyn Chee – Cultural Specialist, Navajo Nation Historic Preservation Department Consultation Meeting Navajo Nation and Grand Canyon National Park (Oct. 12, 2006)
6 Hough and Brennan "Architectural Documentation", 85
human forces, direct preservation treatments are developed on a site-by-site basis and focus on preventing collapse.”  

According to the Park Service, deterioration of these structures is caused by “differential thermal expansion and contraction, ultraviolet radiation (direct sunlight), vegetation, dry rot, direct precipitation (moisture), and biological decay are degrading the integrity and stability of the wooden beams.”

7 ibid, 86
8 ibid, 87
Chapter 3: History of Navajo Architecture

The Navajo consider themselves to be a people of the earth. They trace their origins to the natural world and respect the power of nature. This respect for the natural world extends to every part of their culture, influencing all aspects of Navajo life. If the weather changes and their land becomes inhospitable, tribes do not believe it is appropriate to transform the natural landscape to suit their purposes and as a result migrate to a more suitable location. Architecture, material culture and physical alteration of the landscape are the only evidence that remains in a landscape once inhabited by the Navajo. Grand Canyon National Park possesses the wooden architectural remains of a Havasupai and Navajo civilization that once thrived on the south rim of the Grand Canyon.

Pyramidal wooden structures represent the sacred places in nature where the Navajo People began. The Anglicized word hogan is derived from the Navajo

Figure 1: Gobernador Knob in New Mexico. According to Navajo tradition, the form of all pyramidal wooden structures are modeled after the landscape of the birth place of Changing Woman. Image from Stephen Jett, “Navajo Sacred Places: Management and Interpretation of Mythic History” (1995)
words hoo (place or area) and ghan (dwelling or home) literally translating to “home place.”¹ According to Navajo tradition, the first wooden pyramidal forked pole hogan was constructed by First Man and First Woman in the shape of Gobernador Knob in New Mexico to mimic the location of the birth place of their daughter Changing Woman. When Changing Woman left her parents pyramidal hogan for a home of her own, it was in the shape of Mountain-around-which-traveling-was-done. This mountain, a mesa projection in the surrounding range, influenced the shape of her home and was built using horizontal stacked logs to form the cribbed roof hogan.² All subsequent Navajo hogans were built in these forms and this tradition continued into recent history. Today, many Navajo and Havasupai live in European style housing; however, they build cribbed roof hogans for ceremonial and special functions.

The construction of a hogan is a sacred event in Navajo culture. The songs and chants recited during their construction indicate the central role these structures play in Navajo culture. David McAllester describes this relationship in Hogans. He explains:

“In Navajo philosophy, the material world is the result and also the manifestation of the power of sacred words. The words, in turn proceed from thought, and behind thought lies knowledge. The leaders in charge of the construction of the first house are the Sun, the Moon, Talking God, and Calling God. Their songs begin with a celebration of knowledge, thinking, and speaking of the various places where the house materials are found. The sources of material are personified as Earth Woman and Mountain Woman, and the sustenance of future house dwellers as Water Woman and Corn Woman.”³

During the construction of a hogan, Navajo’s follow a specific construction method.

² David McAllester, Hogans: Navajo Houses & House Songs (Middletown, CT: Wesleyan University Press), 13-14
³ Ibid, 20
handed down to them by their ancestors through traditional songs and chantways. Tradition holds that the form and construction materials of Navajo homes are selected by their Gods to create dwellings in the shape of ancestral house forms. The Navajo did not build their homes, rather, they allowed their Gods to live through them and construct homes for themselves. During construction ceremonies, songs would remind the Navajo that they were building homes suitable for their gods. They built “houses with cosmic ground plans, spacious structures of dawn, jewels [and] cloud”.  

4 Ibid, 15
Chapter 4: Navajo and Havasupai Wooden Pyramidal Structures: Hogans, Wickiups and Sweatlodges

Figure 2: Pyramidal wooden Native American hogan (822) located in Grand Canyon National Park. Photo by Michael Shoriak, October, 2011.

Figure 3: Pyramidal wooden Native American sweatlodge (847b) located in Grand Canyon National Park. Photo by Michael Shoriak, October, 2011.
Navajo and Havasupai structures take two geometric forms. Pyramidal hogans and wikiups are associated to the male members of the Navajo and Havasupai community and cribbed or stacked log hogans are associated with the female members of the community group following ancestral chantways. Hogans and wikiups are the names associated to male dwellings in the Navajo and Havasupai tradition respectively. Pyramidal hogans and sweatlodges are built following traditions that stipulate the selection and arrangement of wooden forked pole primary structural members and their placement in locations based on the four cardinal directions. An excerpt of the Chief Hogan song describes this process:

Along below the east, Earth’s pole I first lean into position. As I plan for it it drops, as I speak to it it drops, now it listens to me as it drops, it yields to my wish as it drops, Long life drops, happiness drops into position, ni yo o.

Along below the south, Mountain Woman’s pole I next lean into position. As I plan for it it drops, as I speak to it it drops, now it listens to me as it drops, it yields to my wish as it drops, Long life drops, happiness drops into position, ni yo o.

Figure 4: Plan view of a model of a pyramidal wooden Native American sweatlodge located in Grand Canyon National Park. Primary Member locations are indicated by colored stakes. Secondary members (not pictured) are laid on top of the 4 primary members forming a pyramid. Model and photo by Michael Shoriak, October, 2011.
Along below the west, Water Woman’s pole I lean into position. As I plan for it it drops, as I speak to it it drops, now it listens to me as it drops, it yields to my wish as it drops, Long life drops, happiness drops into position, ni yo o.

Along below the north, Corn Woman’s pole I lean into position. As I plan for it it drops, as I speak to it it drops, now it listens to me as it drops, it yields to my wish as it drops, Long life drops, happiness drops into position, ni yo o.

In corbeled or stacked log Hogans, Juniper or Pinyon pine logs were stacked horizontally in a hexagonal or octagonal pattern and roofed with smaller wooden poles and tree bark. While occupied, both pyramidal and stacked log structures were covered with a mixture of soil and tree bark to shelter the inhabitants from the harsh environment of northern Arizona.

In the Navajo and Havasupai way of life, family groups would migrate to the canyon floor during the summer to cultivate and harvest crops and back up to the canyon rim during winter months to graze and herd their animals. Seasonal community camps constructed by the Navajo and Havasupai are comprised of a
collection of wooden structures that have a specific function in the lives of these people. Pyramidal wickiups and hogans were used for a variety of different purposes including residences, shelters and food storage. Sweatlodges are smaller versions of pyramidal forked pole structures and were used for bathing and ritual cleansing. Sweatlodges were generally built away from the other structures in a secluded location. Rocks were heated outside the sweatlodge and brought into the structure to heat the interior space causing the inhabitants to sweat. Following their use, rocks would be discarded in piles outside of the sweatlodge. Forked pole pyramidal structures were also covered with smaller branches and juniper bark and the plastered with mud to seal off the outside environment.

Figure 6: Photomerge plan view of Sweatlodge (287) showing the rock discard pile in the surrounding landscape. This sweatlodge was covered with sheet metal instead of the more tradition soil and tree bark. Photographs and photomerge by John Hinchman, October, 2011.
**Pyramidal Forked Pole Structures Located in Grand Canyon National Park**

Figures 7-9 document pyramidal forked pole structures surveyed in October, 2011. For each structure, the primary member locations are indicated with colored stakes using the terminology used in Navajo tradition. They are as follows: Brown Stake – Earth Woman’s Pole (East), Red Stake – Mountain Woman’s Pole (South), Blue Stake – Water Woman’s Pole (West) and Yellow Stake – Corn Woman’s Pole (North).
Figure 7: Wooden Pyramidal Native American Structures

Hogans and Wikiups

Site 694

Site 822

Site 847c

Sweatlodges

Site 287

Site 760

Site 847b
Figure 8: Hogan and Wikiup Primary Member Identification

Site 694
Earth Woman’s Pole (East)     Mountain Woman’s Pole (South)     Water Woman’s Pole (West)     Corn Woman’s Pole (North)

Site 822
Earth Woman’s Pole (East)     Mountain Woman’s Pole (South)     Water Woman’s Pole (West)     Corn Woman’s Pole (North)

Site 847c
Primary Members are Living Trees
Primary Members are Living Trees
Primary Members are Living Trees
Primary Members are Living Trees
Figure 9: Sweatlodge Primary Member Identification

Site 287
Earth Woman’s Pole (East)     Mountain Woman’s Pole (South)     Water Woman’s Pole (West)     Corn Woman’s Pole (North)

Site 760
Earth Woman’s Pole (East)     Mountain Woman’s Pole (South)     Water Woman’s Pole (West)     Corn Woman’s Pole (North)

Site 847b
Earth Woman’s Pole (East)     Mountain Woman’s Pole (South)     Water Woman’s Pole (West)     Corn Woman’s Pole (North)
Chapter 5: Monitoring Visual Change in the Engagement and Fixity of Structural Members

The first proposition is that it is possible to measure physical change in the disposition of primary structural members using non-contact dimensional measurement methods, such as comparative scaled rectified photography and a system of grids that are applied to the image through software manipulation. The method uses rectified photography with control points to achieve a level of dimensional repeatability each time the site is documented from the same location. Post site visit analysis overlays of a grid onto the images allows for photographs from recent and prior site visits to be compared to determine if the position of the primary structural members have shifted relative to each other.

Conventional recording and documentation of structures in association with archaeological sites relies on methods developed for archeological and
ethnographic research. Although these surveys are invaluable in understanding the
cultural significance of sites through a descriptive analysis of the material culture,
they do not provide the architectural conservator with information about material
or environmental changes of the structures over time. Recent digital recording
programs now implemented at an increasing number of National Park Service sites
promise a maximum capture of resource information for all present and future needs.
LIDAR scans produce digital point clouds that can then be converted to vector
drawings providing accurate documentation of each site. But these scans are time
consuming and costly and still require subjective manipulation to convert the point
clouds to line drawings which inhibits their ability to be used as a monitoring tool.
Even assuming scan locations have been marked for repeat scans from the same
location, their effective use for detecting sub millimeter movement or change are
dependent on a great many other factors and therefore they are unlikely to be useful
for a long term monitoring plan.

Scale models of the wood forked pole pyramidal structures were constructed
following both the oral tradition of the Navajo people and the configuration of
structures observed during a field visit to Grand Canyon National Park in October,
2011. The models were manipulated to mimic the shifting of the forked pole
primary structural wooden members that are a precursor to collapse. Photographs
were then taken from specific locations around the models to determine that
the application of a grid in image manipulation software is a viable method for
monitoring the change in position of the primary structural members in the scale
models.
The first step in a program to monitor Native American wooden structures in Grand Canyon National Park is to develop a rapid and non-contact method to document any changes in the engagement and fixity of the primary structural members of the structures. Change in engagement of the members at the apex, or in the length of the members or in the fixity of the members where set in the soil, will result in shifting of displacement of the apex of the structure. Structures that have shifted may cause the forked ends of the primary members to no longer fully engage with one another, their stability relying instead solely on the contact between the primary members and surrounding soil. Displacement is therefore a leading indication of loss of structural stability; continued displacement will ultimately lead to collapse.

Documenting changes in the engagement and fixity of primary members allows identification of structures or principle members that require further investigation. Structures compromised by a loss of engagement of loss of fixity are more susceptible to collapse by external conditions such as loads from snow, wind or flash moving rain water runoff. Short intense periods of heavy rain in the summer and collected snowfall in the winter are capable of undermining the foundational stability of the wooden forked pole primary members by soil erosion.

The proposed survey method must be efficient enough to allow for the monitoring of hundreds of documented sites on the south rim of the Grand Canyon while also providing some form of repeatable representation that can be used to track visible change over time. Native American consultation provides the final and most important restriction for the monitoring plan. The Navajo and Havasupai
have requested that these structures not be physically interfered with in any way due to their ancestral associations the tribes. No markers or movement monitors may be placed on the structures to aid in the identification of movement of the primary members. Photographic targets are the basis for the use of repeated photography in architectural documentation to monitor change of selected architectural features. Photographs of an architectural feature are taken over a period of time and rectified based on permanent control points affixed to the feature. Since this method is not possible or even desirable under the current agreements, targets must be placed around the structures in locations that can be precisely duplicated over successive site visits. Photographic locations must also be controlled with regard to horizontal position relative to the structures (x) and also to the vertical height above the ground (y).

Accurate and repeatable documentation of wooden forked pole Native American structures producing images of the structures from the same location and orientation over time is the foundation of the proposed structural monitoring method. Lab testing with scale models in a controlled environment suggests that movement of the forked pole primary members of greater than 6 inches is a reliable prediction of unstable structures. Although movement of the primary members of less than 6 inches indicates some level of structural instability, the difficulty in accurately generating the same image over successive site visits precludes attempting to monitor pyramidal wooden structures at this resolution. Therefore, the proposed method for monitoring visual change relies on a 1’ x 1’ grid with 6” inch divisions. Definitive identification of the movement of primary structural members from one
grid to the next is the basis for this technique. Although documentation errors may enter the visual monitoring method at any point in the process, at a 6” resolution, the cumulative effect of these errors does not inhibit the accurate detection of changes in structural configuration. It is estimated that camera and grid locations can be repeated to within 1” of the location of previous site visits.

Proposed Field Survey Method

Rapid assessment of the wooden Native American forked pole structures from fixed locations around the site using high resolution 35mm digital photography might allow for sufficient visual comparisons over time. Images taken from the same location, height and angle allow for the recognition of changing features from one visit to the next. The same camera location, height and angle can all be controlled through the use of a standard light weight monopod (single leg tripod) and fixed camera attachment, necessary for access across difficult terrain. A target placed either in front of or behind each structure determines the viewpoint to a specific location around the structure, allowing for visual comparison of the structures from designated viewpoints and controlled time periods.

Pyramidal structures present a variety of difficulties in the face of standard architectural recording and monitoring. There are no orthogonal planes to aid in orientation to a particular structure during successive visits. Standard description based on a particular elevation (north, south, east and west) is elusive due to the curve of the exterior wall where it meets the soil. Therefore, the only way the Park
Service can expect to produce photographic documentation of these sites over successive visits by potentially different researchers is to designate a series of control points around the structures so that both the camera and the target are located in the exact same position for each monitoring event.

Drawing from the previous discussion of the symbolic importance of the primary structural members to Navajo and Havasupai traditions and their contribution to the structural stability of wooden pyramidal forked pole structures, documentation and monitoring will focus on the primary members. The first step in the process is to identify and flag the primary structural members. Flags of different colors (Wood Woman Pole – Brown, Mountain Woman Pole – Red, Water Woman Pole – Blue and Corn Woman Pole – Yellow) are inserted into the ground at a safe distance from the structure not to disturb the site.

Figure 11: East/North elevation of a scale model of a sweatlodge located in the Grand Canyon National Park. Four primary forked members support the intact secondary structure. The total height of the scale on the right is 3 feet.
Figure 12: Plan view of the same scale model. Structural members are marked with flags whose colors represent the different primary members. Wood Woman-Brown, Mountain Woman-Red, Water Woman-Blue and Corn Woman-Yellow. Model and photo by Michael Shoriak.

Figure 13: Perspective of sweatlodge model with the target pole positioned in the appropriate location relative to the Wood Woman Pole. Model and photo by Michael Shoriak.
Construction flags with thin wire stems are preferable due to their minimum impact to the site. These flags will not only orient the viewer of these pictures to the structure, they will also serve as the origin point for selecting the location of the target and camera positions. It may be difficult for different National Park Service staff to locate the same primary members as in previous site visits, however, the target and camera location pins will serve as a guide after the first site visit.

Distance from each of the flag locations will vary from site to site based on the view shed possible given the surrounding environment and topography. Instead of a traditional pin or nail, a length of copper pipe will be driven into the soil marking both the location and orientation of the target. The length of this pipe will be determined in the field based on soil depth and other site factors. A simple pipe cutter will be brought in the field to individually fabricate each camera and target location pin. The specially designed monopod base and target pole base will have a groove drilled into the bottom of the pole and will fit into this pipe and rest on a bolt that has been attached perpendicular to the pipe marker. This way, the orientation and height of the target will be the same during every site visit. A bubble level installed on both the monopod base and target pole will serve as a cross check for changes in orientation of the marker due to frost heave or erosion. Only four markers are needed for each site that will determine the location of the camera and target pole. The marker can be capped and covered with a rock so that no trace of human intervention is visible after Park Service staff leaves the site. Four overlapping photographs will be taken from the same location around the site.
with the same target in the image each time.

The target also serves an additional function. The target pole consists of a 1’ x 1’ square centered on a 3’ tall pole. A target is formed by the connection of two lines emanating from the midpoint of each of the four lines that make up the square. This dimension, as well as the target location and orientation are fixed for each visit as determined by the first monitoring visit. ¾” copper pipe soldered together will form the standard target pole ensuring that the target pole maintains its exact dimensions between site visits. The photographic images produced during successive site visits with the target in a fixed location can be brought into a layout software (Adobe InDesign) and a digital grid applied to the image off site to aid in the detection of changes in structural configuration. The digital grid aids in the detection of small changes in configuration by allowing for the comparison of small, discrete units in
the image. The grid is a particularly powerful tool for detecting shifts in structural engagement and fixity which foreshadows structural collapse. The squares are in the same location for each visit which also makes this an excellent tool for monitoring change of the secondary members.

These images can be compared with field copies of a previous visit’s documentation photographs for a quick assessment of changes in structural configuration of the site. Once back in the office, a layout software will be used to represent images of different site visits together as well as serving as a platform from which to apply the digital grid for more detailed analysis. These documents then become a dated monitoring record for each site to enable future comparisons. Structures found to have documented shifting will be flagged, and with the combination of additional documented factors intrinsic to each site, interventions will be developed to monitor and/or mitigate structures in danger of collapse. Examples of the type of documentation produced are given in Figures 19-22.
Figure 15: Simulated documentation photograph of the first site visit to a sweat lodge using flags to represent the primary members and the target and camera locations marked by 4 target pole bases. Model and photo by Michael Shoriak.

Figure 16: Simulated documentation photograph of the second site visit to a sweat lodge shot from the same location as Figure 12. The primary members have shifted to mimic deterioration. Model and photo by Michael Shoriak.
Figures 17 & 18: Site visits one and two pictured with a digital grid overlaid on the image using Adobe InDesign.
Example Survey Documents

Figures 19–22 are examples of photodocumentation generated using the proposed survey method to Monitor Change in Engagement and Fixity of Wooden Pyramidal Native American Structures. The example uses a scale model to represent a sweatlodge located in Grand Canyon National Park.
Native American Pole Structures

Grand Canyon National Park, U.S.A.

MICHAEL SHORIAK, MASTER OF SCIENCE IN HISTORIC PRESERVATION THESIS

Figure 19: Example baseline documentation photographs and layout.
Native American Pole Structures
Grand Canyon National Park, U.S.A.

MICHAEL SHORIAK, MASTER OF SCIENCE IN HISTORIC PRESERVATION THESIS

Figure 20: Example primary member location key.
Figure 21: Example comparison of baseline documentation and 2nd site visit.

Native American Pole Structures

Grand Canyon National Park, U.S.A.

MICHAEL SHORIAK, MASTER OF SCIENCE IN HISTORIC PRESERVATION THESIS

Comparison of Baseline and 2nd Site Visit

Scale: 1" = 1' 0"

Date: June 15, 2012

Drawn By: Model Constructed by Michael Shoriak
Figure 22: Example comparison of baseline documentation and 2nd site visit with applied grid.
The second proposition is that the visible and concealed material condition of the wood primary structural members can be determined using Infrared Thermography. Infrared Thermography measures the distribution of surface temperatures on the surface of an object. A hand held infrared camera, similar in size to a conventional visible light camera, captures a thermogram of the distribution of temperatures on an object’s surface. A thermogram is an image representing a series of temperature readings with an applied color gradient to visually represent the relationship between the temperatures of different areas of the object. Hidden defects, such as deterioration related loss of core section, are identifiable under laboratory conditions using active thermography. Recent developments in Infrared Thermography technology have dramatically increased the sensitivity and resolution of infrared cameras while also reducing the cost of the cameras. A lab protocol for assessing material anomalies such as a loss of wood density and voids from wood decay has been developed to suggest that improvements in infrared technology enables the non-contact and non-destructive monitoring of these structures in the field. The limits placed on the preservation of these structures by Native American consultation are transformed into an opportunity to develop nondestructive testing techniques for historic wooden structures.

The developed methodology for testing the applicability of Infrared Thermography also relies on the use of proxies in the lab for making observations about the core material condition of the wooden forked pole primary structural
members using an infrared camera on wood samples of known deterioration. The proper selection of samples was based on a study of the properties of the Juniper and Pinyon pine members used to construct wooden Native American structures in Grand Canyon National Park. Properties such as microstructure, density and thermal conductivity of Juniper and Pinyon pine were ascertained through research and lab testing to inform the proper selection of wood samples.

Following the selection of suitable proxy wood samples, a laboratory procedure was developed under controlled conditions. Sound and deteriorated samples were compared under active thermal conditions to see what external factors may affect results such as temperature, relative humidity and moisture. Deteriorated samples were represented by drilling core holes of varying diameters to mimic different levels of deterioration. Larger holes represent a higher level of deterioration following published and observed deterioration patterns in Juniper fence posts. In addition to the detection of deterioration within wooden members, a method for comparing infrared images is outlined that allows for the comparison of images taken under different environmental conditions. Comparison of infrared images taken under different conditions is essential in order to monitor changes in the material condition of forked pole primary structural members of wooden Native American structures in Grand Canyon National Park.

Methods for monitoring and determining the condition and structural stability of pyramidal wooden forked pole structures located in Grand Canyon National Park are severely limited due to the request by the Native American community that the structures not be sampled or touched in any way. Conventional testing methods
such as resistance drilling for wood and wooden structures rely on destructive sampling to analyze a section of the wood material in question and extrapolate those findings to the rest of the wooden member. Advances have been made, however, in the field of nondestructive testing (NDT) of lumber for quality control in saw mills and in the production of wood composite materials. These facilities are external environments where conditions change seasonally and are influenced by many outside factors. Infrared Thermography (IR) has garnered considerable attention over the past decade to grade and sort lumber and wooden composites.¹ This is a rapid, non-contact method to determine subsurface defects and voids by measuring the surface temperature of lumber as it travels through the mill. The following chapter provides an overview of the development of IR technology for nondestructive testing and its suitability for use in assessing Native American wooden structures located in Grand Canyon National Park.

¹ Bucur, Voichita, Nondestructive Characterization and Imaging of Wood (Berlin: Springer, 2003)
Voichita Bucur argues that the origin of nondestructive testing of wood occurred in the early 20th century. In *Nondestructive Characterization and Imaging of Wood*, Voichita explains that scientists initially became interested in the measurement of the elastic properties of wood through the use of mechanical bending. Prior to this period, the only means for understanding the properties of a particular piece of wood was through destructive investigations. Mechanical compression or bending to the point of failure was necessary to determine the strength of wooden elements. Acoustic vibrations were then developed in Europe to study the elasticity of wooden samples by inducing molecular rotation or vibration.\(^2\) Today, many lumber mills and wood processing facilities employ a stress-rating machine for in line grading of lumber products. As a piece of lumber moves through the mill, a machine applies pressure to the lumber to estimate the modulus of elasticity by determining the resistance of the lumber to deflection. Although this method produces an accurate estimation of the properties of lumber moving through the mill, it is a time consuming and expensive process and is not suitable for the monitoring of Native American wooden structures.\(^3\)

There are a variety of tools available today that can nondestructively measure certain physical properties of wood samples. Bucur describes ionizing radiation, infrared thermography, microwave imaging, ultrasonic testing, nuclear

\(^2\) ibid, 1-8

\(^3\) Chi-Leung So, Brian Via, Leslie Groom and Laurence Schimleck et al., "Near Infrared Spectroscopy in the Forest Products Industry" *Forest Products Journal* Vol. 54 No. 3 (March, 2004) 13
magnetic resonance and neutron imaging in his review of nondestructive techniques currently being used to determine wood properties.\textsuperscript{4} Each of these processes relies on the ability of the respective device to detect and visually represent different wavelengths of electromagnetic energy emitted from a wood object. Electromagnetic radiation is passed through the wood sample and captured by a device that has the ability to map the intensity and variation of electromagnetic energy in a specific wavelength. Nondestructive techniques, such as nuclear resonance imaging, have the ability to produce detailed representations of the physical characteristics of a wood sample; however the necessary equipment is not easily transportable. Infrared thermography is the only technique available today that is portable enough to be taken into the field and used to identify interior decay in wood.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{schematic.png}
\caption{Schematic of the relationship between the different wavelengths and energy levels of the electromagnetic spectrum. From http://9-4fordham.wikispaces.com/Electro+Magnetic+Spectrum+and+light. Accessed April, 2012}
\end{figure}

\textsuperscript{4} Bucur, Voichita, \textit{Nondestructive Characterization and Imaging of Wood}, 1-8
Infrared Thermography

Infrared Thermography is the measurement of the wavelength of electromagnetic radiation emitted from the surface of an object in the infrared spectrum. All objects emit some form of electromagnetic radiation based on the physical properties, both macroscopic and microscopic, of the object as well as the properties of surrounding materials and the energy available in the surrounding environment. For example, the black ink printed on this paper absorbs all light in the visible spectrum and our eyes perceive the absence of emitted light as the text on the page. The text acts as a blackbody or “an object that absorbs all the radiant energy impinging on it and reflects and transmits none.”\(^5\) Visible light, however, is only a small portion of the electromagnetic spectrum and there are many different types of electromagnetic radiation that are not visible to the human eye. Radio signals are characterized by electromagnetic waves of a low frequency and long wave length and can travel for great distances undetected by our senses. X-rays, on the other hand, are characterized by electromagnetic waves of a short wavelength and high frequency. As an x-ray passes through a material, it changes the energy of the electrons in that material causing damage.

Infrared thermal energy is emitted by all objects above absolute zero or \(-459^\circ\) Fahrenheit.\(^6\) The sun is the most important generator of radiant thermal energy affecting Earth; however, other sources emit radiant thermal energy such


\(^6\) Kaplan, *Practical Applications*, 10
as the heat radiated by a fire or incandescent lights. Infrared thermal energy is just outside the visible spectrum of electromagnetic radiation in terms of wavelength and frequency. This is why it is possible to feel heat and not see the electromagnetic energy generating the thermal energy emitted from an object.

Herbert Kaplan describes the history of thermal sensing in The Practical Applications of Infrared Thermal Sensing and Imaging Equipment. Kaplan explains that William Herschel was the first person to measure thermal energy in the beginning of the 19th century. Using a prism and a set of thermometers, he discovered that the temperature of the different colors of light transmitted through the prism were proportionally related to each other. Furthermore, he discerned that the proportional rise in temperature of the emitted colors from violet to red continued beyond red in the visible spectrum. In fact, Herschel documented the highest recorded temperature beyond the red light.\(^7\) Hershel paved the way for all future nondestructive testing through the measurement of infrared thermal energy from the surface of an object and all future thermal imaging technologies are based on the

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\(^7\) ibid, 5
same principles he discovered in the 19th century.

Infrared thermography is the measurement of the distribution of infrared thermal energy emitted from the surface of a material. All matter emits thermal energy at a temperature above absolute zero or -459°F Fahrenheit. Below this temperature there is insufficient thermal energy to induce molecular rotation or vibration. Thermal energy emitted from materials above 238°F (388 K) is visible in both the visible and infrared spectrum. This is why the sun appears yellow in the sky and an electric stove glows red when it is hot. Infrared energy below this temperature and wavelength is invisible to the unaided eye and is only felt as heat.

Infrared measurements of surface temperature can be displayed as thermograms which depict the intensity of thermal energy radiated from the surface of an object at one point in time. Thermograms are displayed in two ways: qualitatively through the measurement of the surface radiant energy contrast in an object’s surface, or quantitatively through recording the apparent surface temperature distribution of the surface of an object. Infrared thermal detectors located inside thermal cameras convert this thermal energy into an electrical signal that corresponds to a calibrated temperature. Infrared measurements are non contact and nondestructive.

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8 ibid, 10
9 Kaplan, Practical Applications, 10
10 Kaplan, Practical Applications, 5
Active Infrared thermography measures the distribution of temperatures on the surface of an object following an external injection of thermal radiation (heat). As thermal energy passes through a wooden object, differences in the internal structure of wood produce identifiable thermal patterns that correspond to variations in the density of the sample. Passive thermography utilizes thermal energy already available in the surrounding environment such as the sun or the heating of wood during processing in a saw mill. P. Meinlschmidt describes the differences between thermograms generated by active and passive thermography in “Thermographic Detection of Defects in Wood and Wood-Based Materials”. He explains:

If material under inspection is heated with radiators (active thermography), the temperature of the surface will rise suddenly. The speed at which the heat front dissipates into the material depends on thermal properties like density, heat capacity, thermal conductivity and the bonding quality between top surface layer and the base material. A defect in the subsurface creates a barrier for the heat diffusion process and, therefore, the surface temperature above the defect will decrease more slowly than the temperature in other regions. The surface above such defect will show a hot spot for a longer time as its vicinity covering good bonding material...In contrast to the fast dissipation of heat in metallic materials, the dissipation of heat in wood-based-materials is comparably slow. The detection of defects can take a few seconds or even some minutes after the heat impact depending on the material and depth of the defect. If the inspected material is heated during the production process (passive thermography), the surface temperature will decrease after leaving the production line. Invisible defects within the material will appear as cold spots on the surface, because of the good insulation between the hot core material and the colder surface. In both cases, active or passive thermography, the defects can be either detected as hot (active) or cold spots (passive) on the surface.11

The forest products industry has recognized the possibility of implementing infrared thermography for the processing and grading of lumber and paper products. 1994 saw the first experiments published in the Forest Products Journal using infrared thermography to detect knots in lumber for grading purposes. In “Locating Knots in Wood with an Infrared Detector System”, Franklin Quin, Jr., Philip

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Steele and Rubin Shmulsky describe the first applications of infrared technology for knot detection. Quin et al. conducted experiments using radiant heat to excite the wooden sample surface before attempting to detect knots in the lumber samples. They found that knot detection using radiant heat required long periods of time before knots became visible in the thermogram. That same year, Murata and Sadoh used incandescent lamps to heat hinoki lumber samples for 60 seconds to produce a thermogram showing the location of knots based on the differing thermal properties of knots and clear wood. They found that after the 60 second heating cycle the denser knot material was 1.8°F colder than the surrounding wood material. Also in 1994, Steele and Quin heated southern yellow pine lumber in a hot press at 250°F for 300 seconds. Temperatures of the pine samples were measured as the samples cooled and they found that knot temperatures were on average 8°F higher than the surrounding clear wood.

In 2003, a patent was issued to Steven Kelly for a “Method for Predicting Mechanical Properties of Wood”. Kelly devised a system of comparison between samples with known decay and unknown samples by using both visible and near infrared spectra. Reference spectra were created for a particular species and compared to spectra from unknown samples. The spectra from unknown samples were then related to the reference spectra to predict the mechanical properties of the unknown decayed sample. This allowed for the nondestructive analysis of

12 Franklin Quin, Philip Steele and Rubin Shmulsky, "Locating Knots in Wood with an Infrared Detector System" Forest Products Journal Vol. 48 No. 10 (October, 1998) 80-84
13 Quin et al. “Locating Knots in Wood”, 83
wood samples with unknown levels of decay.15

2004 saw the first mention of coupling Near Infrared Spectroscopy and Multivariate Analysis in “Near Infrared Spectroscopy in the Forest Products Industry”.16 Multivariate Analysis allows for the comparison of known physical and chemical properties of a wood sample with near infrared (NIR) spectra of samples of the same species. Techniques such as principal component analysis and partial least squares analysis allow for the quantitative analysis of the chemical properties of wood samples. Quantitative analysis of chemical properties can then compared to known data and expressed in physical and mechanical properties without conventional destructive testing.17 Mention is also given of the uncontrolled factory environment and how changes in temperature and relative humidity can influence NIR readings. The authors suggest that temperature has more of an effect on NIR readings than relative humidity.

Laurence Schimleck et al. describe their utilization of near infrared spectroscopy for estimating wood properties in “Near Infrared Spectroscopy for the Nondestructive Estimation of Clear Wood Properties of Pinus taeda L. from the Southern United States”.18 The purpose of the 2005 Schimleck article was to determine if surface texture or data collected from cross-sectional or radial surfaces of juvenile or mature wood, had any adverse effects on testing. They found that

17 ibid, 8-9
differences between data obtained from different samples was small, however, the best results were obtained from sanded cross-sectional surfaces. The Schimleck et al. article also provides a literature review of all pertinent testing related to using near infrared spectroscopy to estimate wood properties. The following description of the development of NIR spectroscopy in the wood products industry comes from this article.\textsuperscript{19} In 1995, Hoffmeyer and Pederson used NIR to non destructively determine moisture content, specific gravity, compression and bending strength and chemical and biological degradation of Norway spruce. Their results showed that analyzing the cross-sectional surface of Norway spruce samples provided an accurate representation of unknown wood properties. Gindel et al. used commercially available boards of European larch for testing and generated high correlations of density, bending strength, modulus of elasticity and compressive strength from sanded radial surfaces. A number of descriptions of successful experiments with NIR and wood properties follow with generally the same results: NIR spectroscopy is an effective nondestructive method for determining unknown wood properties.

\textsuperscript{19} ibid, 22
Chapter 7: Material Factors Affecting Infrared Thermography of Structural Members of Native American Wood Structures

Native American structures of the Navajo and Havasupai peoples in Grand Canyon National Park were built according to methods and materials of construction that were handed down through an oral tradition. Each structure was framed with 3 or 4 wooden forked pole primary structural members which were embedded into the earth corresponding to the cardinal directions. The opposite forked ends were interlocked forming the apex of the pyramidal structure. Secondary members were not structural and functioned as cladding. The proposed use of infrared thermography to monitor the condition of the primary members of these structures will be affected by several material and environmental factors. This chapter discusses those factors.

Physical and Mechanical Properties of Wood

The physical and mechanical properties of a wood sample are dependent on the particular composition and structure of the species of wood being studied. The structure and composition of wood is a complex arrangement of organic materials into a porous biological structure. Variations between the major classes of trees, conifers (softwoods) and angiosperms (hardwoods) produce woods that are light and porous as well as woods that are extremely dense and durable. Wood is an orthotropic material meaning that trees have 3 mutually perpendicular axes of
symmetry. These axes cut through the tree in the longitudinal (from the roots to the
crown), radial (cut horizontally through the trunk) and tangential (tangent to growth
rings) directions. Wood is also anisotropic with physical and mechanical properties
that vary according to the previously describes axes. Therefore, wooden structural
members perform differently in longitudinal, radial and tangential orientations.
Wood is also a hygroscopic material and the equilibrium moisture content of wood
is dependent on the relative humidity of the surrounding environment. In northern
Arizona, the estimated average moisture content of exterior wood is 9% due to the
low ambient relative humidity of the dry desert climate. Wood reaches the fiber
saturation point at approximately 30% moisture content when free water begins to
form in the individual wood cells. Variations in moisture content in wood will result
in anisotropic dimensional change being dependent on the directional specific
coefficient of hygroscopic expansion/ contraction.

The average chemical composition of wood is as follows: 50% Cellulose
– A linear polymer of glucose which gives wood its form and strength; 20–25%
Lignin – a 3D phenylpropane matrix which glues together the individual cellulose
components; 20–25 % Hemicellulose – simple sugars that bond Lignin and
Cellulose; 1% Extractives – secondary chemicals found in the heartwood derived
from the metabolic wastes of living cells (Extractives give wood species their
characteristic color, odor and decay resistance); 1% Ash – earth elements.

1 The following description of the structure of wood is derived from a Conservation Science Lecture by
Joe Loferski at the University of Pennsylvania School of Design, 12/2/2011
2 US Forest Product Laboratory, “Moisture Content of Wood In Use” USDA Forrest Service Research Note
FPL-0226,(Forrest Products Laboratory, Madison, WI, 1973)
Wood Species – Utah Juniper (Junipeus osteosperm)

Havasupai and Navajo builders selected specific wood species for the construction of wooden pyramidal forked pole structures. Juniper and Pinyon pine wooden poles were the only two species utilized due to their form, bifurcation and forked branches, as well as their spiritual significance. In hogans, trunks of juniper trees were used for the forked pole primary structural members. Juniper wood possesses a high level of decay resistance and the long straight trunks with forking branches associated with this species are well suited to this purpose. Suitable trunks were either collected from the forest floor or cut down from living trees. During construction, one end of the juniper pole was buried in the soil and the forked end would be interlocked with a corresponding primary member forming a pyramid. Once the 3 or 4 pole primary structure was assembled, the final form of the hogan would be constructed using both Juniper and Pinyon pine trunks and branches. The hogan was then covered in soil and Juniper bark. Sweatlodges were built primarily from juniper branches and trunks. The Navajo and Havasupai believe that Juniper wood absorbs the escaping spirits released during ritual cleansing inside the sweatlodge. Ponderosa pine, although prevalent in some areas of Grand Canyon National Park, is not typically used in construction of pyramidal structures.

In Grand Canyon National Park, structural members have been documented by Park surveys as being Utah Juniper (Junipeus osteosperma) and to a lesser extent Pinyon Pine (Pinus edulis) based on visual characteristics and nearby living species. Of these two species, Pinyon Pine is classified by the USDA Forest Service
as a non durable wood meaning that pine posts are not decay resistant without preservative treatment embedded in the earth for an acceptable period of time. USDA Studies testing the service life of untreated Pinyon Pine posts embedded in the earth have found that they rarely last for more than 4-6 years. Therefore for the purposes of this thesis, it is then assumed that the forked pole primary structural members supporting the surviving hogans, wikiups and sweatlodges in Grand Canyon National Park are Utah Juniper or a related Juniper species due to material durability and likelihood of overall survival.

Utah Juniper is a softwood or gymnosperm meaning that the living tree produces exposed seeds in cones. Trunks and branches of Juniper are composed of a series of longitudinal cells or tracheids. Tracheids make up 95% of the composition of softwoods while the remaining 5% are rays. The tracheids are grouped together tightly in the longitudinal direction, similar to the grouping of a handful of straws in the palm of the hand. Although tracheids have closed ends, they enable the transport of moisture vertically in a Juniper trunk or branch through capillary action. Pits allow radial transport of moisture between individual tracheids. Moisture and food transport occurs through a series of rays that radiate from the core of the tree (pith) horizontally towards the bark. Moving from the core of the tree outward, all trees have a pith, heartwood (dead wood cells), smaller sapwood portion (living wood cells), cambium (which produces wood and bark), and bark.

3 Ronald Barger and Peter Ffolliott, *Physical Characteristics and Utilization of Major Woodland Tree Species in Arizona* USDA Forest Service Research paper RM-83 (Fort Collins, Colorado: Rocky Mountain Forest and Range Experiment Station, 1972) 26
Wood is an organic material and under the right conditions it will decay. Decay fungi will attack any wood species if food, moisture, air and heat are present in the right quantities. Without any one of these factors, wood will not succumb to decay fungi. The United States Department of Agriculture lists Utah Juniper as a decay-resistant species due largely to its high extractive content. Juniper contains 8.8% extractives compared to 1% extractives for most wood species. Extractives are a mix of chemicals that are toxic to decay fungi and insects and are found in the heartwood of trees. This makes the heartwood of juniper posts extremely resistant to decay without preservative treatment while also giving freshly cut wood a “cedar” smell.

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4 Ronald Barger and Peter Ffolliott, *Physical Characteristics and Utilization of Major Woodland Tree Species*, 34
Physical and Mechanical Properties of Juniper

The mechanical properties of all wood species are a function of wood density. Density “is the mass contained in a unit volume of a material, and specific gravity is the ratio of the density of the material to the density of water. Specific gravity is also called relative density.”5 In Physical Characteristics and Utilization of Major Woodland Tree Species in Arizona, Roland Berger and Peter Ffolliott determined the density of Utah Juniper following the U. S. Forest Products Laboratory’s analytic procedures. They obtained core samples from a variety of woodland tree species, including Utah Juniper, and calculated the relative density of extracted and unextracted wood cores.6 Extracted cores have had their extractives removed by chemical processes. The specific gravity of unextracted increment cores for Utah Juniper in the 0-10.9 inch diameter class developed by Berger and Ffolliott; this species and diameter closely resemble the species and diameters encountered in the primary structural members in Grand Canyon National Park.7 The mean specific gravity determined during their study from 14 samples was 0.548. For comparison, the density of many commercially important softwood species available in the United States are as follows: Ponderosa Pine - .44; Western red cedar - .31, Black Spruce - .41.8 Western larch with a specific gravity of .55 is the only commercially

6 Ronald Barger and Peter Ffolliott, Physical Characteristics and Utilization of Major Woodland Tree Spe-cies, 14
7 Ibid, 69
available softwood with a comparable density to Utah Juniper.

The high density of Utah Juniper informs the analysis of the material condition of wooden forked pole primary structural members in two separate ways. First, Juniper posts used in pyramidal structures are durable and decay resistant in the environment of Grand Canyon National Park and are more durable and decay resistant than any other commercially available wood species for wooden posts due their higher density and extractive content.

Second, with regard to the suitability of Utah Juniper for nondestructive monitoring using Infrared Thermography to identify the presence of hidden interior deterioration, the high density of Utah Juniper makes this species efficient in the transfer of thermal energy through a wooden member. Close packing of tracheids increases the thermal conductivity of Utah Juniper allowing for the movement of thermal energy across the wood section in a short time period and the high thermal conductivity of Utah Juniper makes this species suitable for non contact and non destructive infrared thermography.

Environmental Factors Influencing Decay

The dry environment of Northern Arizona affects the properties of Juniper poles used in the construction of pyramidal forked pole structures. The moisture content of wood in a living Juniper tree may vary from 50-150% depending on the location within the tree and season.° Once a limb is removed from a tree either

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9 George Tsoumis, *Science and Technology of Wood*, 128
due to natural causes or in preparation for use in a Native American structure, the moisture content of the limb decreases dramatically until it reaches equilibrium with the environment. In Grand Canyon National Park, the average moisture content of exterior wood is 9%. The dramatic decrease in moisture content from living tree to pole primary structural member causes shrinkage cracking and checking as wood members rapidly dry out, creating differences in moisture content between the heartwood and sapwood of softwood species. Moisture content of heartwood has been found to be 50% or greater than that of the sapwood in a variety of softwood species. In the transition from a living state to dead state, differences between the moisture content of the interior and exterior portions of Juniper poles causes internal stresses and cracking along the heartwood and sapwood boundaries creating checking and voids to allow the infiltration of water into the core of a wooden member.

Decay Pattern of Utah Juniper Forked Pole Primary Members: George Meagher’s Arizona Fence Post Study

The Havasupai and Navajo recognized the decay resistance and vulnerabilities to checking of untreated Juniper posts and utilized them for the forked pole primary structural members in their wooden pyramidal structures. Early European settlers soon learned of the remarkable decay resistance of untreated

10 Forest Products Laboratory, “Moisture Content of Wood In Use” USDA Forrest Service Research Note FPL-0226,(Forrest Products Laboratory, Madison, WI, 1973) 4
11 George Tsoumis, Science and Technology of Wood, 128
Figure 26: Average moisture content of a Juniper Pole from Living Tree to Forked Pole Primary Member in a Wooden Pyramidal Native American Structure. Moisture content of forked pole primary members also fluctuates due to weather and atmospheric conditions.
Figure 27: All of the Juniper posts collected from Grand Canyon National Park display checking and cracking as a result of the rapid decrease in moisture content after a limb is removed from a live tree. Checking radiates from the pith to the outside of wood samples. Based on tree ring data, this limb was approximately 190 years old when it was removed from a living tree. The high density of Juniper is a result of this slow growth rate.
Juniper posts and began using them as fences in Arizona. The US Forest Service began a systematic study of the decay resistance of untreated Juniper posts in 1939 under George Meagher. In *Service Life of Untreated Juniper and Cypress Fence Posts in Arizona*, Meagher selected a range of Juniper and Cypress fences that could be precisely dated in a variety of different climactic and soil conditions. 97 fences were monitored, 37 of Utah Juniper, beginning in 1939. The study was divided into different environmental zones which influenced the decay of untreated poles due to variations in temperature and moisture. In Meagher’s study, the woodland zone defined as landscapes with pinyon, juniper, oak and chaparral associations with intermediate temperature and moisture, closely resembles the environment of the South Rim of Grand Canyon National Park. Meagher surveyed approximately 25 posts in each of the 97 fences and recorded information about pole size, heartwood diameter, sapwood condition, site context and condition of the post as determined by the ability of the post to withstand a lateral pull of 100 pounds. Meagher arrived at several conclusions that inform the present study of Native American wooden pyramidal pole structures in Grand Canyon National Park. First, he found that all three Juniper species studied, Utah, One Seed and Alligator Juniper, are equally serviceable in the woodland zone. This finding alleviates the need to precisely identify the Juniper species in pyramidal Native American wooden structures in Grand Canyon National Park. Second, Meagher found that after 40 years of service, 80% of Juniper fence posts of all diameters were still serviceable.

12 George Meagher, *Service Life of Untreated Juniper and Cypress Fence Posts in Arizona* (Tuscon, Arizona: Souhtwestern Forest and Range Experimental Station, 1940) 1-2
13 ibid, 2
14 ibid, 4
and after 50 years 74% were serviceable. Therefore, based on Meagher’s study, one may reasonably conclude a maximum of 74% of the Juniper forked pole primary members used by the Navajo and Havasupai between 1880 and 1950 of the same diameter as Meagher’s posts are still serviceable. Finally, Meagher made the recommendation of a minimum of 4 inches in heartwood diameter for posts in the woodland zone. He found that the sapwood of all juniper species was not durable, and the service life of posts was dependent entirely on the diameter of decay resistant heartwood.

The heartwood of Juniper achieves its decay resistance due to the presence of a high amount of extractives which are toxic to decay fungi. Tropolones are seven-membered carbon ring compounds found in the extractives of Juniper that give this wood its decay resistance. A variety of these tropolones are found in Juniper heartwood and “are concentrated in the outer heartwood, with only traces near the pith”. Judging by the location of extractives in only certain areas of Juniper poles, a typical decay pattern may be assumed. The sapwood is first to decay (80% of the test posts in Meagher’s study had no remaining sapwood after 20 years of service) leaving only the heartwood core. The inner core of the remaining heartwood is next to decay due to a lower concentration of extractives around the pith. Based on this assumed decay pattern, poles from structures dating to the beginning of the 20th century would contain only the outer heartwood of the

15 ibid, 5
16 ibid, 9
17 Ronald Barger and Peter Ffolliott, Physical Characteristics and Utilization of Major Woodland Tree Species, 26
18 George Meagher, Service Life of Untreated Juniper and Cypress Fence Posts in Arizona, 5
original pole with the sapwood and inner pith removed by decay fungi.

George Meagher’s study of dated fence posts provides an indication of the probable condition of Juniper forked poles used in Native American wood pyramidal structures in Grand Canyon National Park. Sweatlodges located in the Park are more susceptible to decay related collapse due to a smaller cross section of heartwood relative to the larger hogans and wikiups at the time of their construction. The average documented age of the pyramidal forked pole structures in Grand Canyon National Park is between 72 and 130 years old. Untreated Juniper poles exposed to the environment of Grand Canyon National Park are decay resistant, however, after a 50 year service life, only 74% of the fence posts in Meagher’s study were still serviceable. Therefore, by extension, it may be presumed that many of the Juniper forked pole primary members in the remaining
pyramidal structures are approaching the end of their service life and a method is needed to identify primary members where decay has undermined their structural stability. Lastly, Meagher’s study indicates that the decay pattern of Juniper posts conceals the internal decay of the primary member from visual inspection because extractives concentrated around the external surface of Juniper heartwood causes Juniper posts to deteriorate from the inside out creating hollow cylinders of wood as the forked pole primary members decay. Therefore, a non-destructive technique is needed with the capability to identify hidden internal voids in Juniper posts if one is to non-destructively assess the in situ condition of the primary structural members of Native American pyramidal structures.
Infrared thermography measures the distribution of surface temperatures on an object. Heat, as defined by Herbert Kaplan, is energy in transition. Heat is generated by a variety of sources including the sun, fire and incandescent bulbs. The surface temperature of an object is not a measurement of internal temperature but rather a property of matter that is in a state of flux due to differences in heat balance with the surrounding environment. As thermal energy is applied to an object, it will flow from an area of higher temperature to an area of lower temperature until the object reaches thermal equilibrium.

There are three mechanisms for the transfer of thermal energy. Conduction is the transfer of thermal energy in a stationary media such as a solid, liquid or gas that occurs due to atomic vibrations that transfer energy one molecule at a time from higher temperature locations to lower temperature locations. Convection is the transfer of thermal energy between a solid and a stationary or moving fluid or gas (as part of convection, conduction is taking place at the interface of direct contact between the two). This occurs naturally during the interaction of the ocean, land and sea breezes. Radiation, the most important heat transfer mechanism for infrared thermography, occurs due to electromagnetic emission and absorption of thermal energy. This type of heat transfer can occur in a vacuum, occurs at the speed of light and is proportional to the fourth power of the temperature difference between the objects. Radiation occurs in the Infrared portion of the electromagnetic
spectrum from 375 µm to 100 µm.

When the surface of an object is heated by an external energy source by means of radiation heat transfer the radiated energy travelling from the heat source travels by electromagnetic radiation to the surface of the object where the thermal energy is either reflected from the surface or emitted from the surface to a cooler object. Radiant thermal energy that is absorbed by the object will be transferred from the surface to the body of the object, presuming that the surface is hotter than the body and assuming that radiant gain is greater than convective cooling at the surface. The surface characteristics of the sample will dictate the interaction of the emitted heat and the sample surface.

Figure 29: Schematic showing the interaction of radiant heat and a wooden sample stack. Wood has a rough surface and much of the radiant energy that hits the surface is absorbed by the wooden sample stack. Transmitted heat is the focus of infrared thermography to detect interior voids in wooden forked pole primary members. Graphic adapted from Herbert Kaplan, Practical Applications, pgs. 13-14.
The radiant heat transfer is affected by a number of factors. A rough surface, like wood, will disperse IR radiation and absorb thermal energy. Wood, for example, absorbs much of the radiant energy it comes into contact with and has an emissivity of .90. Metals, on the other hand, reflect a large portion of radiant heat and have a much lower emissivity.

Radiant heat transfer can also be used to measure the surface temperature of an object, as well as to heat it. The surface temperature of an object can be measured using a thermal camera. Thermal cameras are an extension of the radiation thermometer due to how the thermal camera transforms and represents information about the surface temperature of an object by measuring the heat or thermal energy radiated from the surface. The thermogram produced by a thermal camera incorporates many measurements of thermal radiation into a single image that has been color coded to show differences using a color scale that corresponds to surface temperature differences.

The radiant thermal energy input into an object may rely on surrounding, natural or uncontrolled sources of thermal energy such as the sun; this is known as passive infrared thermography. Alternately, a controlled source of radiant thermal energy (such as an infrared lamp) may be used, particularly when a controlled or steady state condition is required; this is known as active thermography. Variations in surface temperature can occur due to variations in radiant heat gain/loss at the surface or due to variations in convective heat loss away from the surface into the surrounding air. Variations in surface temperature will also occur as a result of subsurface geometry of the object, which in turn affects the transfer of thermal...
energy away from the surface and into the body of the object. Assuming that the radiant heat transfer rates and convective heat transfer rates are uniform over the surface, then the subsurface geometric variations will be the dominant cause of variations in surface temperature. In this instance, variations in surface temperature become the means to detect geometric changes, particularly voids, in the object. For example, a sample with a large void will transmit thermal energy across its cross section by radiant heat transfer at a faster rate than conductive heat transfer through a homogenous solid sample object of the same outside dimensions. This is because there is less mass to heat in the object with the void, resulting in a higher temperature being developed on the opposite side from the heated surface. In the case of significant voids, internal radiant heat transfer between the void surfaces may be a significant factor in elevating the temperature of the opposite exterior surface or “far” side of the object. The transmission of thermal energy through a sample is also influenced by the physical state of matter through which the heat must travel through.

The difference in the rate between the two types of heat transfer creates differences in the thermal patterns of surface temperatures on the back or transmitted face of an object, thus indicating the presence of mass discontinuities (voids and cracks) or changes in the thermal conductivity of the solid material (such as caused by density or moisture content changes).
Heat Transfer in Wood

Wood is a porous material. Tracheids composed of cellulose are glued together by lignin and hemicellulose resembling, on a microscopic level, a group of drinking straws held together by a rubber band. As thermal energy moves through a piece of wood, it is transferred on a microscopic level, through solid cellulose material and the cavities created by cell walls which are filled with air and moisture vapor (or water, if saturated). Conducive heat transfer occurs in the cellulose and radiation occurs in the cell cavities. Wood generally has a low thermal conductivity. Increased density and extractive content can increase thermal conductivity, but with an increase in mass and the added mass that must be heated; as a result, more thermal energy must be applied to a dense object than a less dense object to bring them to the same temperature.

The measurement of the rate at which heat passes through a material is expressed as thermal conductivity. The Wood Engineering and Construction Handbook defines thermal conductivity as “heat energy in British units transmitted each hour through a panel of material 1 ft² and 1 inch thick for each 1°F temperature differential on opposite sides of the panel.”
Thermal conductivity is calculated for woods up to 40 percent moisture content and perpendicular to the grain by the following equation:

\[ k = S (1.39 + 0.028M) + 0.165 \]

where: 
- \( k \) = thermal conductivity, Btu\(\cdot\)in/hour\(\cdot\)ft\(^2\)\(\cdot\)°F
- \( S \) = specific gravity based on volume at current moisture content and weight when oven dry
- \( M \) = moisture content expressed as a percentage of oven dry weight

Two unknown variables in this equation can be estimated based on information gathered from the literature survey conducted for this thesis. Ronald Barger and Peter Ffolliott’s, *Physical Characteristics and Utilization of Major Woodland Tree Species* determined the specific gravity of Utah Juniper samples following the U.S. Forest Products testing procedures. They report that the mean specific gravity determined from 14 unextracted core samples in the 0-10.9 inch diameter class was 0.548.

Specific gravity is a dimensionless ratio defined as the ratio of the density of the material to the density of water at a specified temperature. The second unknown variable, moisture content expressed as a percentage of oven dry weight, comes from the environment of Grand Canyon National Park. USDA Forest Service Research Note FPL-0226 states that the average moisture content of exterior wooden elements in the southwest United States is 9 percent. Therefore,

\[ k = (0.548) (1.39 + 0.028\cdot 0.09) + 0.165 \]

\[ k = 0.928 \text{ Btu}\cdot\text{in}/\text{h}\cdot\text{ft}^2\cdot\text{°F} \]

This is a high value in comparison to the average thermal conductivity of 0.80
Btu•in/h•ft²•°F for coniferous wood samples given in the *Wood Engineering and Construction Handbook*. This is due to the high specific gravity (and by relationship density) and extractive content of Utah Juniper that increases the thermal conductivity of this wood species above that of other coniferous tree species.

Variations in the external environment or density of individual wooden members have an effect on the thermal conductivity of wood samples. The above calculation was based on the average moisture content of external wood in the Southwest. If the moisture content of the wooden member is raised due to a weather related event, the thermal conductivity will also increase. For example, using the same equation, samples with 20% moisture content will have a thermal conductivity of 0.929 Btu•in/h•ft²•°F and samples with a moisture content of 35% will increase furthermore to 0.932 Btu•in/h•ft²•°F. Conversely, a decrease in moisture content will lower the thermal conductivity of juniper samples. A sample with a moisture content of 2% will have a thermal conductivity of 0.927 Btu•in/h•ft²•°F. Density and by relationship specific gravity also influence the thermal conductivity of juniper samples. A increase in specific gravity to 0.600 at 9% moisture content will increase the thermal conductivity to 1.00 Btu•in/h•ft²•°F while a decrease in specific gravity at the same moisture content to 0.400 will decrease thermal conductivity to 0.722 Btu•in/h•ft²•°F.
Recent advances in Infrared camera technology are now making it possible to use them as an effective diagnostic tool for detecting internal voids in wood members. Today’s commercially available cameras are portable and light weight and can be used in the field at Grand Canyon National Park.

The first infrared imaging technologies were developed by the United States military beginning in the 1940 for use in night vision systems. The first cameras were infrared scanners which produced an in line scan of the target surface. Scanners operated either by scanning moving targets which would advance the scanners field of view or by a system of mirrors which could be adjusted to move the field of view around one stationary object. 1963 saw the introduction of the AGA Thermovision real time thermal imager that weighed over 70 lbs. The cameras required the use of external cooling systems and scanning optical systems which made these cameras heavy and unwieldy. FLIR introduced another type of thermal scanner in the 1960s that was attached to an airplane’s fuselage and could create aerial infrared maps by using a “push-broom” approach to scan the earth’s surface. This technology was also large due to the associated cooling and scanning systems.

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1 Kaplan, *Practical Applications*, 6. The following history of thermal camera technology follows the timeline set for in *Practical Applications*.
2 Ibid, 6
Mitsubishi produced the first infrared focal plane arrays with staring capability that no longer required the use of scanning technologies. This was the first step in making thermal cameras smaller and more compact. Computer technology helped to further improve thermal cameras in the early 1990s by allowing for the export of digital thermograms that could then be manipulated with computer diagnostic programs. The final development in the evolution of thermal cameras occurred in the mid-1990s with the manufacture of cameras which no longer required cooling systems to increase the sensitivity of their detector systems. These cameras use uncooled microbolometric and ferroelectric detector arrays to produce real time thermal images without the use of scanning systems. More recently, thermal cameras are being further refined and developed by the US military as well as by other government agencies such as NASA for material analysis. The price and size of thermal cameras has decreased with each passing year while the sensitivity of commercially available cameras has increased dramatically. Thermal cameras can now be found as standard equipment in some automobiles which has greatly reduced the cost of thermal cameras due to increased production.\footnote{FLIR representative lecture at the University of Pennsylvania, December, 2011}

Infrared cameras operate by focusing radiant energy on to a detector surface that has the capability to transfer the received infrared radiant energy into electrical signals which are then converted into temperature measurements. By focusing the target radiant energy on the detector, spot radiometers have the ability to measure
surface spot temperatures with great accuracy. Infrared cameras combine this ability with the capability to scan a target surface in the camera’s field of view to “produce thermal maps or thermograms where the brightness intensity or color hue of any spot on the map is representative of the temperature of the surface at that point.” Thermal cameras operate as a collection of spot radiometers to measure the temperature distribution of the surface of the target object.

When viewing a sample surface with a thermal camera there are three types of energy that may or may not be reaching the camera’s detector from the sample surface. These radiant energy sources are reflected energy, transmitted energy and emitted energy. The total proportion of all of the energy reaching a thermal detector is calculated by:

\[
\%\text{Emitted Energy (We)} + \%\text{Reflected Energy (Wr)} + \%\text{Transmitted Energy (Wt)} = 100\% 
\]

Emitted energy provides an accurate measurement of the sample surface temperature and reflected and transmitted energy must be reduced or accounted for to accurately measure surface temperature. With regard to thermal imaging, there are three types of target surfaces that affect the accuracy of thermal cameras to measure surface temperature. These surfaces are called blackbody, grey-body and non-greybody surfaces. The difference between these surfaces is the amount of thermal energy reflected from their respective surfaces, or emissivity. A blackbody is a theoretical material that absorbs all of the radiant energy that comes

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4 Kaplan, Practical Applications, 15-16
5 Ibid, 15
6 Ibid, 19

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in contact with its surface. This would be the perfect surface to analyze using a thermal camera because, assuming that the surface is also completely opaque, all of the energy that reaches the detector would be emitted energy. Measurements of greybody surfaces, such as wood, require an emissivity correction that in today’s cameras occurs within the camera through a software correction. Non-greybodies require much more complicated correction calculations to filter out reflected radiant energy.

Transmitted thermal energy is generally seen as a hindrance to obtaining accurate surface temperature measurements. If one is simply concerned with or has access to one sample surface, transmitted energy passing through an object will influence the surface reading based on the type of energy, hot or cold, passing through.

Figure 30: Schematic comparing using a thermal camera to map the surface temperature of the heated face of a sample column and mapping the surface temperature of the transmitted surface of the sample column. While mapping the heated face, the thermal camera focuses all of the thermal radiation in the Field of View (FOV) and filters out the reflected heat. On the transmitted face, only transmitted thermal energy is mapped by the thermal camera.
through the object. However, if one is interested in the interior structure of a sample, transmitted energy can tell you a great deal about internal voids in an otherwise solid sample. The testing conclusions and recommendations for field monitoring are based on the ability of the selected thermal camera to measure not only the radiant energy emitted from a sample surface but also the transmitted energy that passes through a sample due to a controlled thermal injection.

All commercially available cameras produced today are based on detector mosaics or staring infrared focal plane array technology developed by FLIR in the 1980s. These cameras use a collection of infrared detectors to visually map the surface of a sample. Today’s focal plane arrays are similar to current digital camera technology only that with a thermal camera, the pixels are temperature measurements instead of dots of color. The capability of all thermal cameras in use today is a function of the resolution and sensitivity of the detector. Cameras currently available offer a range of infrared image resolutions ranging from $120 \times 120$ (14,400 individual spot temperature measurements) to $320 \times 240$ (76,800 individual spot temperature measurements) detector sizes. Thermal cameras also have a limited field of view (FOV) and, like visible light cameras, can capture only what falls within that cone of view.

7 Ibid, 27
Chapter 10: Methodology for Laboratory Testing of Infrared Void Detection in Wood

Figure 31: Tools and samples. Douglas fir proxy samples and Juniper samples used during laboratory testing pictured with the IR heat source, tripod, background and thermal camera.
This chapter describes the laboratory methodology developed to test the feasibility of using infrared thermography to detect voids in wood samples similar to the principal structural members of pyramidal Native American structures. Since access to Juniper samples used in Native American structures in Grand Canyon National Park is prohibited, proxy samples were constructed from Douglas fir lumber commercially available in Philadelphia, Pennsylvania. The dimensions of the proxy samples were based on measurements taken in the field of actual wood primary members used in Native American pyramidal structures located in Grand Canyon National Park. The design of the lab testing procedures was finalized using these Douglas fir samples and further testing was conducted using samples that were collected in Grand Canyon National Park gathered under the supervision of National Park Service staff. In the initial stages, the lab environment was controlled in order to achieve the best visual representation of surface temperature. During the conclusion of lab testing, however, control of the environment was relaxed in order to better mimic possible field conditions while imaging juniper samples.

Samples were made from standard 4” x 4” x 8’ untreated Douglas fir fence posts milled to a cylindrical profile with a diameter of 3 ¼”. The 8’ Douglas fir cylinder was then divided into smaller cylinders of different lengths that could be used as both control cylinders and test cylinders. 5 ½” long wood cylinders were used as the base cylinder, cap cylinder and control cylinder for each experiment. These cylinders were not cored to mimic deterioration. Test cylinders were 6” long with cores of increasing diameters drilled through the middle of the cylinder. An additional 1” sample divider was made to separate the controls from the test sample.
in each sample stack. Sample stacks were comprised of a 5 ½” base cylinder, a 6” test cylinder, a 1” sample divider, a 5 ½” control cylinder and a 5 ½” cap cylinder. Stacked together, these samples stacks served as proxies for Juniper samples used as primary members.

All of the control cylinders remained solid and the test samples were cored with a drill press with bits of increasing diameter to mimic deterioration. The following 8 drill bit diameters were used to core the 6” test sample cylinders during this thesis: 2 ½”, 2 ¼”, 2”, 1 ½”, 1 ¼”, 1”, ¾”, ½”. 4 sets of control cylinders and sample dividers were made to be used with the 8 test cylinders. This allowed for the testing of up to 4 test cylinders each day that were at complete thermal equilibrium with the lab environment. 3 Juniper sample stacks were also made with wood collected from Grand Canyon National Park with the same sample dimensions as the Douglas fir proxy samples. The Juniper sample diameters were 4 3/4”, 2” and 2 1/4”. Each Juniper sample was cored with two holes for lab testing. The 4 3/4” Juniper sample was cored with a 1 1/2” bit and a 2 1/4” bit, the 2” sample with a

![Sample Stacks with Void Diameters between 2 1/2” and 11/2”](image1)
![Sample Stacks with Void Diameters between 11/4” and 1/2”](image2)

Figure 32: Plan and exploded plan views of all of the Douglas fir proxy sample stacks used during laboratory testing with different cylinders labeled.
3/4” and a 1” bit and the 2 1/4” sample with a 1” and 1 1/2” bit.

The heating element used in the laboratory tests consisted of two 375 Watt IR bulbs mounted on a wooden light stand which oriented the bulbs horizontally toward the sample stack. Sample stacks were located 10 ½” away from the sample surface to the IR bulbs and were placed on a tripod mounted on a cart to allow for the movement of the sample stack away from the heat source in order to acquire the best possible thermal image. After the sample stack was heated for a 5 minute interval, the cart was wheeled back and positioned in front of a cooler plywood background.¹

This cooler background increased thermal contrast, and allowed the capture of detailed thermograms by using the FLUKE Smartview software to focus

¹ Plywood sheets were left outside during cold Philadelphia winter days or a piece of cardboard was used that was left under an air conditioning vent as the weather warmed during the Spring.
the selected infrared temperature range solely on the sample stack and not on a background that was at the same temperature. For example, the ambient air temperature in the Architectural Conservation Laboratory kept most nonmetallic surfaces in the lab at a temperature of approximately 71°F. If the thermal images were not captured in front of this cooler background, as the thermal range was narrowed in the Smartview software to the selected thermal gradient, infrared information would be displayed on both the sample stack and the background. As testing progressed to using actual juniper wood samples, these environmental controls were relaxed to better mimic assumed field conditions.
Figure 35: Laboratory Testing Procedure

Step 1
Sample stack is positioned in front of IR heat source and heated for 5 minutes.

Step 2
Sample stack is moved away from the heat source in front of a plywood sheet that has been cooled down below ambient room temperature. This step allows for better scaling of the thermal image.

Step 3
A thermal image is taken of the heated face of the sample stack in front of the cool plywood sheet.
Laboratory Testing Procedure Continued

Step 4
The sample stack is rotated on the tripod base so that the transmitted face of the sample stack faces the thermal camera.

Step 5
A thermal image is taken of the transmitted face of the sample stack in front of the cool plywood sheet.

Step 6
The sample stack is repositioned in front of the IR heat source and testing resumes for another 5 minute interval.
The camera used for all infrared testing in this thesis was the FLUKE Ti32-10060557 Thermal Imager. This camera has a 320 x 240 uncooled micobolometer focal plane array. This camera was generously loaned to me during my work by the University of Pennsylvania Facilities Department who uses this camera for electrical and building systems diagnostic testing. The temperature measurement range for this camera is -20°C - 600°C with an accuracy of +/- 2°C at 25°C. The thermal sensitivity of this camera allows for the detection of temperature variations of .004°C on a sample surface. This camera has a field of view of 23’ x 17’ and a minimum focus distance of 18”. The Fluke Ti32 camera captures both an infrared thermogram of emitted thermal energy between 7.5 μm to 14 μm wavelengths and

![Comparison of thermal images](image)

Figure 36: Comparison of thermal images captured with a controlled background temperature on the left, and an uncontrolled background temperature on the right.
also a visible light image of the same field of view. FLUKE cameras also have a patented IR Fusion technology that allows for the storing of a full visual image which can be displayed, blended and stored for with each IR image. Thermal and visual images can be presented simultaneously as a full thermal image or as a Picture-In-Picture (PIP) image in various blend modes. This feature greatly enhances the ability to depict both real time and computer enhanced thermographic images allowing for the isolation of thermal anomalies on a sample surface.

Figure 37: Fluke Ti32 Camera and accessories used in this thesis.
The FLUKE Ti32 has the ability to export a variety of common file formats including .bmp and .jpegs as well as FLUKE .is2 files that can be manipulated with the included SmartView software. Visible light and IR images are stored after each picture on a SD memory card which can be plugged directly into a computer using the included adapter. The SmartView software allows for post image capture adjustments of the thermal image including IR image and visible light image focus, spot measurement labels, and temperature scaling to focus on a very specific temperature range on the sample.

Visible light and thermal images were taken of both the heated (front) and transmitted (back) surfaces of wooden samples over 5 minute intervals for a total cycle of 15 minutes for each sample stack. The FLUKE Ti32 Thermal Imager captures both the visible light and thermal images simultaneously with push of one button. After each 5 minute interval, the sample stack was positioned in front of the cooler background and a visible light and thermal image was taken of the heated face first and the tripod was rotated to capture a thermal image of the transmitted face of the sample stack. The whole assembly was then returned in front of the heating element and another 5 minute heating cycle commenced. The total time between each heating cycle was approximately 2 minutes for all sample stacks.

A total of 6 visible light and thermal images were captured for each sample stack containing a test sample cylinder with one of the eight void sizes drilled through the core of the test cylinder. This process was repeated for each of the 8 test cylinders and the native .is2 format files were imported into FLUKE’s Smartview software. The software was used to scale all of the thermal images to the same
temperature range to allow for comparison across samples. The thermal range for
the heated face of the sample column was between 70°F and 135°F and between
70°F and 74°F for the transmitted face. The distribution of surface temperatures is
represented by a color gradient similar to that used in meteorological forecasting
where yellows and reds indicate high temperatures and greens and blues represent
lower temperatures. Surface temperatures falling outside of this range on the low
end, or below 70°F do not receive a temperature color and those outside of this
range on the high end, above 135°F on the heated face and 74°F on the transmitted
face are represented by the color white.

Figure 38: Comparison of thermal images with different temperature scales. On the left side, the thermal gradient was
computed by the camera to include all surface temperatures in the camera’s field of view. On the right side, the thermal
gradient has been set to between 135°F and 70°F for the heated face and between 74°F and 70°F on the transmitted
face.
For the same rate of thermal energy input, sample sections with internal voids are identifiable by hot spots on the transmitted face of the samples due to lower total mass and the increased rate of heat transfer by both conduction and radiation as opposed to the solid sections with higher mass and only the slower method of the two, conduction. The following Figures 39-44 show a comparison of the lab results for each of the sample stacks imaged with the thermal camera. The Results chapter evaluates the results of the laboratory tests.
Chapter 11: Results of Laboratory Testing

Figures 39-46 compare the results of laboratory testing using the Ti32 FLUKE thermal camera to identify voids in Douglas fir proxy sample stacks and sample stacks of Utah Juniper collected from Grand Canyon National Park. The location of the test cylinder within each sample stack is represented by the 3-D model in the center of the Figure as a cylinder with an interior void and is the second 6” cylinder from the bottom of the sample stack. Figures 39-41 compare four sample stacks with different diameter holes drilled though the core of the test cylinder. Figures 42-44 compare two Juniper samples with different sized cores drilled through the test cylinder. The images on both the left hand and right hand margins represent the diameter of the void in the test cylinder, the location of the heat source and the camera location. The heat source is symbolized by the bulb icon and the thermal camera location is symbolized by the camera icon. The group of thermal and visible light images on the left side of the layout contains images of the heated face of the sample after each 5 minute heating interval. Moving left to right the images are as follows: (1) visible light image of the heated face of the sample stack, (2) thermal image of the heated face of the sample stack after a 5 minute heating interval, (3) thermal image of the heated face of the sample stack after a 10 minute heating interval, (4) thermal image of the heated face of the sample stack after a 15 minute heating interval. Notice the gradual expansion of the warmer red areas on the sample stack as the stack is heated progressively longer. Heat is evenly distributed across the sample stack. The group of thermal and visible light images
on the right side of the layout contains images of the transmitted (back) face of the sample stack after each 5 minute heating interval. Moving left to right the images are as follows: (1) visible light image of the transmitted face of the sample stack, (2) thermal image of the transmitted face of the sample stack after a 5 minute heating interval, (3) thermal image of the transmitted face of the sample stack after a 10 minute heating interval, (4) thermal image of the transmitted face of the sample stack after a 15 minute heating interval.

Sample stacks in Figures 39-44 are arranged by the percentage of the void diameter in relation to the diameter of the original sample stack. Percentage of the void diameter to the original sample stack is calculated by the diametric ratio of void to solid or (Void Diameter/ Sample Diameter) %. They are grouped as follows:

Figure 39: 4 - 3 1/4” diameter Douglas fir proxy samples with void diameters greater than 45% of the original member diameter

Figure 40: 4 - 3 1/4” diameter Douglas fir proxy samples with void diameters less than 45% of the original member diameter

Figure 41: 4 - 3 1/4” diameter Douglas fir proxy samples with void diameters greater than 45 % of the original member diameter filled with tightly packed wood shavings

Figure 42: 2 - 4 3/4” diameter Utah Juniper samples with void diameters between 32% and 47% of the original member diameter.

Figure 43: 2 - 2” diameter Utah Juniper samples with void diameters between 38% and 50% of the original member diameter.

Figure 44: 1 - 2 1/4” diameter Utah Juniper sample in the path of thermal energy with void a diameter of 67% of the original member diameter compared to 1 Douglas fir proxy sample with void diameter of 69% the original member diameter.
Figure 39: IRT Test Results: Douglas fir proxy samples with void diameters greater than 45% of the original member diameter.
Figure 40: IRT Test Results: Douglas fir proxy samples with void diameters less than 45% of the original member diameter.
IRT Test Results: Douglas fir proxy samples with void diameters greater than 45% of the original member diameter. The void has been densely packed with wood shavings to understand the affect deterioration debris has on infrared testing.
Heat Source
Camera Viewpoint

Figure 42: IRT Test Results: 4 3/4" diameter Utah Juniper sample with void diameters of 32% and 48% of the original member diameter.
Figure 43: IRT Test Results: 2 1/4" diameter Utah Juniper sample with void diameters of 38% and 50% of the original member diameter.
Figure 44: IRT Test Results: 2 1/4" diameter Utah juniper sample in the path of thermal energy with void diameter of 67% of the original member diameter compared to a Douglas Fir proxy sample with void diameter of 69% the original member cross section.
Figure 39 depicts a comparison of Douglas fir proxy sample stacks containing test cylinders with void diameters greater than 45% of the original member section. Test cylinders with four different diameter interior voids drilled through the middle of the test sample cylinder are compared. Beginning from the bottom of the page the diametric ratios giving the percentage of void diameter to the original sample diameter for the sample stacks in Figure 39 are: 2 1/2” void (77%), 2 1/4” void (69%), 2” void (62%) and 1 1/2” void (46%). Thermal anomalies begin to appear on the transmitted face of the test cylinders after the 5 minute heating interval for all of the sample stacks and these areas become progressively hotter as the heating interval continues.

Thermal anomalies or hot spots on the transmitted face of the sample stack indicate areas that have internal voids. This confirms the expectation that for a consistent thermal energy input, members with voids will transmit thermal energy to the back face more quickly because of lower mass and combined conduction and radiation heat transfer. Figure 40 compares the results of testing Douglas fir samples with void diameters less than 45 % of the original member diameter. Moving from the bottom of the page, the diametric ratios giving the percentage of void diameter to sample diameter for the sample stacks in Figure 40 are: 1 1/4” void (38%), 1” void (31%), 3/4” void (23%) and 1/2” void (15%). Notice on this sheet that the ability of the thermal camera to detect heat transmitting through the test cylinder is no longer possible in sample stacks including test cylinders with voids smaller than 38 % diametric ratio between void diameter and sample diameter (1 1/4” void).
The combination of Figures 39 and 40 represent the limitations of the thermal camera to detect transmitted energy through a Douglas fir test cylinder with an interior void in the sample stack. It is important to remember, however, that it is the diameter of the void that governs the ability of the thermal camera to detect interior voids. As the void becomes progressively smaller, thermal energy being transferred through the test cylinder must travel by conduction through a larger section of solid wood. In test cylinders with voids smaller than 1 ¼”, thermal energy does not move through the test cylinder during the allotted test interval (15 minutes) to be detected by a change in temperature on the transmitted face of the sample stack by the thermal camera.

Figure 41 investigates the influence of tightly packed wood shavings in the transfer of heat through the sample stack. The samples in this figure are the same as Figure 39; however, on this sheet the voids in the test cylinder are tightly packed.

![Figure 45: Thermal images of two Juniper samples, one control cylinder (left) and one test cylinder (right) showing heat move through the void at a faster rate than the solid wood section. The interior surface on the opposite surface of the void from the heat source is warmer (82°F) than the top surface of the test cylinder (77°).](image-url)
with wood shavings. The wood shavings act as a barrier to the transmission of thermal energy by radiation across the void. The greater mass of the near solid hollow test cylinders tightly packed with wood shavings reduce the amount of thermal energy transmitted to the back face of the sample. By a void diameter of 2” in the samples in Figure 41, transmitted heat on the surface of the sample stack can no longer be detected by the camera because the change in surface temperature is too small to be detected by the thermal camera. Although the tight packing of wood shavings is not representative of the conditions in the field, this sheet does give some indication of the influence of material within the test cylinder voids. Figures 42-44 compare the results of testing with Juniper samples brought back to Philadelphia from Grand Canyon National Park.

Results of Testing with Douglas fir Proxy Samples

Testing using Douglas fir proxy samples enables some general conclusions about the amount of section loss that is detectable using the heat source and thermal camera used in this thesis. Using a steady state heat source for 15 minutes, voids in Douglas fir members with a diameter of 3 1/2” become detectable in the sample when the void diameter is greater than 38% the original member section. Densely packed fill in the void prevents the detection of voids and void diameters less than 69% of the original member diameter are not detectable using a steady state heat source for 15 minutes.
Calculating the percentage of void diameter to the sample diameter is the key to using this technique to assess the condition of wooden forked pole primary structural members with a wide variety of diameters. The Douglas fir proxy sample stacks were all 3 ¼” in diameter. In the field, structure surveys conducted in October, 2011 recorded primary members with diameters ranging from 2” to 8 ½”. Thermal energy inputs, heating intervals, member diameter and infrared camera resolution affect the ability to image voids using Infrared Thermography. Therefore it is necessary to determine the detection threshold below which voids are too small to be detected and imaged. Once the deterioration threshold for detection is reached, a void diameter of between 38% and 31% of the original sample diameter is indicated by the presence of a hot spot over the void on the transmitted face. Voids were drilled at ¼”increments in diameter during testing and further analysis is needed using smaller void diameter increments to more precisely identify the deterioration threshold where thermal energy from the heat source used in this thesis will begin to radiate from the transmitted surface of the test cylinder.

Physical properties such as density, moisture and extractive content all increase the thermal conductivity of wood. Other properties, including the amount of debris remaining in deteriorated void, also have an influence on the rate at which thermal energy is transferred through a wood sample. Figure 41 depicts the same sample stacks represented in Figure 39; however, in Figure 41, the internal voids have been tightly packed with wood shavings. The rate of heat transfer through the test cylinder is greatly reduced in these sample stacks and internal void diameters of less than 2 ¼” do not allow sufficient heat to pass through the test cylinder.
during the 15 minute heating interval. This type of dense packing of the remains of deteriorated wood is unlikely to occur in the field due to the presence of checking in the primary members, however, it is important to factor the effect of fill material in deteriorated voids into the identification of primary members with a loss of internal section.
Figure 46: Graphic representing 3 1/4" Douglas fir proxy sample with 2 1/2" void drilled through the core. The void diameter is 77% of the original member section and is detectable using a steady state heat source for 15 minutes.

Figure 47: Graphic representing 3 1/4" Douglas fir proxy sample with 1 1/4" void drilled through the core. The void diameter is 38% of the original member section and is the last void diameter detectable using a steady state heat source for 15 minutes.
### Table: Void Diameter/ Sample Diameter

<table>
<thead>
<tr>
<th>Sample Diameter</th>
<th>Diameter of Void</th>
<th>Void Diameter/ Sample Diameter</th>
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**Figure 48:** Graphic representing the visible deterioration threshold at which thermal energy can pass through a 3 1/4" Douglas Fir test cylinder and transmit through the surface of the sample stack with in the 15 minute testing interval. A void diameter of greater than 38% of the original wood section is identifiable using infrared thermography in a laboratory setting. A loss of less than 38% wood section is not identifiable using this lab methodology because sufficient thermal cannot pass through the test sample section during the 15 minute heating interval to raise the transmitted face temperature to a level detectable using a thermal camera.
Results of Testing with Juniper Samples

Lab testing with Juniper samples provides the first quantification of the ability of thermal energy to pass through various diameters of Juniper. The thermal camera is a tool that is sensitive enough to detect small increases in the surface temperature of the transmitted face of tested samples. Following the results of lab testing, it is hypothesized that a percentage of void diameter to original sample diameter greater than 50% is detectable in Juniper samples using a thermal camera and a steady state heat source in a controlled environment. Lab testing has shown that although the proposed system cannot monitor incremental changes in the loss of section of primary members, it can, however, identify primary members that have deteriorated beyond the deterioration threshold: 50% internal void diameter. Field testing is necessary to determine if wooden Juniper forked pole primary structural members used in pyramidal Native American structures in Grand Canyon National Park with void diameters of greater than 50% of original sample diameter are detectable using infrared thermography and a controlled heat source.

Figures 42-44 represent the results of testing using Juniper wood samples collected from Grand Canyon National Park. Based on the findings from the literature review of the physical characteristics of Juniper as described in Ronald Barger and Peter Ffolliott’s, Physical Characteristics and Utilization of Major Woodland Tree Species, it was hypothesized that the rate of heat transfer across Juniper wood sections would be faster based on its higher density and extractive content in comparison to Douglas fir. Testing proved this hypothesis and also determined the
deterioration threshold that is necessary for thermal energy to travel across a Juniper wood section and emit from the transmitted surface of the sample during the 15 minute heating interval. Due to the limited availability of Juniper in Philadelphia, PA, further testing is needed to refine the limitations of detecting loss of section in Juniper wood samples. During testing with Juniper samples, the lab environment and background temperatures for the thermal images were not controlled as in previous testing with Douglas fir samples to better mimic in field conditions. Although there was insufficient contrast between the sample temperature and the background temperature, it is still possible to identify internal voids above the deterioration threshold in the sample stacks.

Figure 42 depicts the heating of a Juniper sample stack constructed with the same proportions as the Douglas fir proxy sample stacks with the exception of the diameter of the sample stack. The diameter of the Juniper sample stack in Figure 42 is 4 ¾”. The top row of thermal and visible light images was taken of the sample stack with a 1 ½” void drilled through the sample which was 32% of the sample diameter. During the 15 minute heating cycle, it is not possible to identify the test cylinder with the void. The bottom row of visible light and thermal images depict the same sample stack, only in this instance a 2 ¼” void has been drilled though the test cylinder. The 2 1/4” void is 48% of the original sample diameter and during the 15 minute heating interval it is possible to detect the presence of an internal void by a hot spot on the transmitted face of the test cylinder. The deterioration threshold for identifying internal voids in the 4 ¾” Juniper sample is between a 32-48% percent void diameter to original sample diameter.
Although it was only possible to drill two different size holes through the test cylinder in the sample stack represented in Figure 42, additional testing with Juniper samples of different diameters should generate similar results due to the physical characteristics of Juniper. Figure 43 compares a 2” diameter Juniper sample with a ¾” void on the top row and a 1” void on the bottom row. The percentages of void diameter to original member diameter in these two samples are 38% and 21/4"/4 3/4" = 48%.
50% respectively. Voids are detectable in the sample with a 50% void diameter to original member diameter.

This diameter of sample in Figure 43 is representative of a primary member one of the smallest structure’s surveyed during our field work in October, Big Jim’s Sweatlodge. This Sweatlodge is unique not only because of the small dimensions of the primary members, but also because the builder used thin gauge copper wire to bind together two smaller members to make one forked pole primary member. Copper wire was wrapped around the cap cylinder in the sample with a 3/4” diameter void and around both the cap cylinder and test cylinder in the bottom row of images of the sample stack with a 1” void. Although the more thermally conductive wire generated a higher surface temperature on the wire and areas of wood that were in contact with it, these thermal patterns are distinguishable from hot spots generated by internal voids that are larger than the deterioration threshold visible using the thermal camera.

Figure 44 compares the results of testing with Douglas fir and Juniper sample stacks. The top row of visible light and infrared images depicts the controlled heating of a Juniper sample that is not circular in cross section. A variety of environmental factors influence the shape and growth patterns of a living tree, and many of the wooden forked pole primary members of structures surveyed in Grand Canyon National Park are not circular in cross section. This sample section is oblong in shape. A hole was drilled in the test cylinder through an off center location due to checking that extends into the pith of the branch. Thermal energy was applied on the wide face of the sample which is 2 ¼” in diameter from the
heated face to the transmitted face of the sample. Care must be taken in the field to understand the form of each primary member surveyed in order to achieve comparable results. Thermal energy applied to the opposite axis of the Juniper sample would have to travel 4 ½” across the interior wood section. Therefore, all field testing must indicate the surface and estimated diameter of the forked pole primary member material to ensure comparable results.

A 1 ½” void was drilled through the test cylinder in Figure 44. The diameter of the sample through which thermal energy must pass is 2 1/4” and the void diameter

![Diagram of Juniper sample with voids](image)
is 67% of the original sample diameter. Following the results of prior testing with juniper samples, a 67% loss of section is greater than the average deterioration threshold established by earlier testing of a 50% void diameter at which thermal energy can transfer through Juniper primary members during the 15 minute heating interval. The results, visualized on Figure 44, are consistent with earlier findings. The bottom row of visible light and thermal images compares the heating pattern of the Douglas fir sample stack and the Juniper sample stack.

Figure 51: Graphic representing 2 1/4" diameter Juniper sample across the heating path. A 1 1/2" void has been drilled off center leaving 33% of the original solid wood section remaining. 67% loss of section is above the deterioration threshold and thermal energy is visible on the transmitted face of the sample after the 15 minute heating interval.
Figure 52: Graphic representing the deterioration threshold at which heat can pass through Juniper cylinders of different diameters. A loss of 48% section is visible using the methods developed during laboratory testing.

<table>
<thead>
<tr>
<th>Sample Diameter</th>
<th>Diameter of Void</th>
<th>Void Diameter/Sample Diameter</th>
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Testing using Juniper samples in the lab has shown that it is possible to detect internal voids that are greater than 50% of the original member section. The applicability of monitoring using infrared thermography is based on the affects of a loss of section below and above the detectable deterioration threshold. Juniper wood used as primary members in pyramidal wood structures have a high capacity in relationship to the relatively small loads acting of these structures. Therefore, large percentages of void to original primary member section are necessary to compromise Juniper pyramidal structures and identification of primary members with between a 50% and 85% loss of wood section is sufficient to identify unstable structures due to material degradation.¹

The implications of a 50% sectional loss of a primary member is calculated by first determining the loss in cross sectional area related to a void diameter of over 50% of the original wood section. For example, a 3.25” diameter Juniper primary member with a 50% void section (void diameter of 1.625”) only corresponds to a 25% loss of cross sectional area. This is a small reduction in material properties relative to the loading of these structures. Barger and Ffolliott determined that the maximum crushing strength of Juniper is approximately 4120 psi.² The theoretical crushing load of a 3.25 OD member with 50% core loss is 4120 psi × (Aod – Aid)si or \[ 4120 \text{ psi} \times 5.12 \text{ si} = 21,102 \text{ pounds} \] (without any safety factors).

¹The following discussion of the implications of section loss to the structural stability of wood pyramidal structures is founded on information provided to me by my thesis advisor, Michael Henry.

² Barger, Ronald and Peter Ffolliott. Physical Characteristics and Utilization of Major Woodland Tree Species in Arizona. 15
Even at 50% capacity, these structures are able to withstand loads much greater than those acting on these structures.

The columnar stability of primary members with greater than 50% section loss is also a consideration for the stability of wood pyramidal structures as a whole. Using the Euler Column Buckling formula, the only variable that changes between calculating the columnar stability of a solid column and a hollow column is the moment of inertia. A solid column with a diameter of 3.25” has a moment of inertia of \( l = 5.47 \text{ in}^4 \) and a 50 % hollow column has a moment of inertia of \( l=5.134 \text{ in}^4 \). This corresponds to only a 6% reduction in columnar stability from a solid column to a 50% hollow column. Detection of primary members with a 50% loss of section is more than sufficient to identify primary members that have lost their columnar stability with all other factors such as elasticity, length and fixity being equal.

The theoretical load required to buckle 50% hollow primary member is calculated using the Euler Column Buckling Formula. A 60” column with modulus of elasticity of 650,000 psi\(^3\) with one end fixed and one end free to move with a moment of inertia of 5.134 in\(^4\) requires 2,915 pounds axial load on the member in order to cause buckling (without a safety factor). The capacity of a 50% hollow column to resist bucking is only 6% less than a solid column. The load necessary to buckle a primary member (2,915 psi) is much less than the load required to crush a primary member in the axial direction (21,102 pounds). Therefore, buckling failure of the primary members is the failure mode that controls the performance of wood pyramidal structures.

Euler’s Column Buckling Formula can also provide an indication of the

---

3 Barger, Ronald and Peter Ffolliott. Physical Characteristics and Utilization of Major Woodland Tree Species in Arizona. 15
theoretical section loss necessary to buckle a 3.25” diameter primary member.

Using a hypothetical load of 500 pounds, a section loss of 3” is necessary to buckle a 3.25” Juniper primary member under a more realistic load. A void diameter of 3” in a primary member 3.25” in diameter is over a 92% loss of section. Juniper trunks and branches used in wood pyramidal structures are not perfect cylinders and a section loss of this magnitude would most likely undermine the stability of primary members due to shell irregularities. Therefore, the detection of a loss of 50% wood section is more than sufficient as a baseline for monitoring the primary members of wood pyramidal structures. The proposed monitoring method using infrared thermography will monitor section losses of between 50% and 85% in wood primary members.
Proposed Field Monitoring Method

In the field, the laboratory method can be adapted to identify interior deterioration of forked pole primary members that have lost more than 50% of their original wood section. A portable heat source (ex. Infrared spot light) will be needed in the field to serve as the controlled heat source. The selection of a safe and portable heat source will be necessary to provide a consistent source of thermal energy; the heat source should not be a potential ignition source for wildfires. This section describes the proposed method to identify interior decay in forked pole primary members used in wooden pyramidal structures in Grand Canyon National Park.

Three different pyramidal structures should be selected for testing using active thermography. Selection of the structures to be tested will occur in the field based on the identification of structures with accessible and exposed primary members. Initial field testing will try to limit external variables that may affect field results including secondary members that may be in the way of either the heat source or the field of view of the thermal camera. Infrared images of the primary members should be taken in the morning before the sun has begun hitting the structure to obtain the best results. The contact point between the wooden forked pole primary members and the soil will be the focus of field testing following earlier survey findings that basal deterioration of the primary members is the most likely cause of the collapse of forked pole pyramidal structures in Grand Canyon National Park. Field testing of primary members will take place after photographic documentation.
of the structure including the identification of forked pole primary members and
the marking of the location of control points around the structure following the
procedures described for monitoring changes in the structural configuration.

Field testing will match as closely as possible laboratory testing procedures.
A heat source with the capability to emit a comparable amount of BTUs as the
heat source used in laboratory testing should be selected. The heat source should
be placed approximately 10 ½” away from the base of an identified forked pole
primary member. One member of the team will operate the heat source ensuring
that it maintains a safe operating distance away from the structure and also keep
track of the timing of the heating cycle. After each 5 minute heating cycle, the heat
source operator will turn off the heat source and the IR camera operator will take
multiple infrared images of the opposite face of the heated primary member. This
may require that the IR camera operator point the camera through a doorway or
opening in the pyramidal structure. Under no circumstances should the IR camera
operator enter the structure to take an IR image. This process is continued for the
entire 15 minute heating interval with thermal images taken each time. All three or
four primary members will be tested this way with voice annotation provided with
each picture about the primary member being tested and how long the primary
member has been heated.

Issues that may arise during testing and questions about image processing
will be resolved after field testing. The appropriate scaling of the thermal images
for comparison of images over successive site visits under different atmospheric
conditions will also be determined after this first site visit. These images will then be
laid out onto a standard graphic template and analyzed as a set. External factors such as determining if changing original primary member surface temperatures affect the ability to compare images of primary members in the same structure will also be studied. In addition to field testing, a full scale model of a pyramidal forked pole wooden structure with known levels of deterioration should be constructed and tested using the same procedures to understand the capabilities and limitations of the proposed testing procedure in identifying interior deterioration of forked pole primary members in an uncontrolled environment.
Recommendations

The results of this thesis provide the National Park Service with a non-contact, non-destructive methodology for monitoring changes in configuration and material condition of wooden pyramidal forked pole structures constructed by the Navajo and Havasupai peoples located in Grand Canyon Nation Park. Testing of the proposed methods for monitoring changes in the fixity and engagement of structural members and material condition of forked pole structures will need to continue. Recommendations are provided below for future testing.

Research conducted for this thesis revealed that George Meagher’s, *Service Life of Untreated Juniper and Cypress Fence Posts in Arizona*¹ and Ronald Barger and Peter Ffolliott’s, *Physical Characteristics and Utilization of Major Woodland Tree Species in Arizona*² provide useful information that can be applied to understanding the environmental vulnerabilities and deterioration of the wood used in Native American wood structures. The service life of untreated Juniper posts embedded into the ground is determined by the size of the heartwood section of the post. Meagher recommends that untreated Juniper used in fences have a heartwood diameter of at least 4” in the woodland zone of Arizona.³ Therefore, smaller structures, such as sweatlodges, are more at risk to deterioration related collapse.

¹ George Meagher, *Service Life of Untreated Juniper and Cypress Fence Posts in Arizona* (Tuscon, Arizona: Souhtwestern Forest and Range Experimental Station, 1940)
² Ronald Barger and Peter Ffolliott, *Physical Characteristics and Utilization of Major Woodland Tree Species in Arizona* USDA Forest Service Research paper RM-83 (Fort Collins, Colorado: Rocky Mountain Forest and Range Experiment Station, 1972)
³ George Meagher, *Service Life of Untreated Juniper and Cypress Fence Posts in Arizona*, 9
Site surveys have provided additional information by the study of collapsed sweatlodges. A combination of basal deterioration of the primary members and their location in water run off zones appear to have caused the collapse of two surveyed sweatlodges, one of which was LIDAR scanned while still partially erect by the National Park Service in 2006. Additional study is necessary to determine the exact cause of structural collapse using both environmental and human related factors though the survey system developed in a companion thesis by Neils Youngborg.

The first recommended method in the proposed dual approach monitoring system for pyramidal structures is to use comparative scaled rectified photography and a system of grids that are applied to the image in the lab through software manipulation to detect changes in the structural configuration of the structures. This thesis used scale models of the site to mimic structural movement and further testing is needed to determine if a field application of this technique will provide the same results. Additional testing should include the construction of a full scale model that is manipulated to mimic changes in structural configuration. The same processes of primary member identification and camera and target location selection should be carried out on the same structure following the creation of known structural shifts. Different surveyors should document changes in structural configuration to determine if the control points are effective in removing surveyor error over multiple site visits. Additional lab testing will also give an indication of the resolution of this method in identifying movement. For example, is it possible to identify a 1” shift in the structural members, or are only 6” shifts in the primary members detectable
using this method? The implications of varying degrees of structural movement must also be further studied. When, for example, is structural movement an indication of impending collapse? Following additional testing and a better understanding of the limitations of this method, it is recommended that a program be implemented to acquire baseline photographic documentation of the pyramidal forked pole structures located in Grand Canyon National Park. The frequency with which the individual structures are monitored will be determined following the identification of at risk sites through the gathering of environmental and structural characteristics that cause the collapse of these structures. A companion thesis by Neils Youngborg, will develop a risk assessment plan to provide the National Park Service with a method of determining at risk structures using environmental factors.

With regard to the proposal to identify interior deterioration of the wooden forked pole primary members through the use of infrared thermography, additional testing with Juniper samples is necessary to better understand the capabilities and limitations of this procedure. Access to Juniper samples was limited due to the distance between Philadelphia and Grand Canyon National Park. Further testing with a wider range of Juniper sample diameters and also Juniper samples of the same diameter will refine the results given above. At this time, lab results indicate that it is possible to detect a loss of approximately 50% wood section or greater using IR thermography and the laboratory methods described above. Additional structural analysis as to the performance of these structures in a variety of environments and weather events will help to determine realistic loads that are imposed on these structures so that the critical section loss leading to collapse can
be better estimated.

Wooden pyramidal Native American structures are located in an uncontrolled environment, not a laboratory setting. The next step in the application of the monitoring program proposed in this thesis is to turn the lab experiment into a feasible field technique. Questions about the effect of temperature and relative humidity conditions, measurement times (summer/winter, morning/afternoon) and surrounding vegetation must be analyzed as to their impact on IR testing results. A portable heat source that can provide the same BTUs in thermal energy must also be acquired. Rechargeable or battery powered visible light or infrared spot lights are one possibility. Additional variables such as distance from the heat source to the Juniper sample and the effect of secondary members in the heat path also need further study.

The question of the safety of this technique for the preservation of Native American wooden structures and also Grand Canyon National Park is central to the application of this monitoring procedure. Surface temperatures generated during lab testing never exceeded the highest temperature of 155° recorded at site 822 during field survey in October, 2011 on the exterior surface of Wood Woman’s Pole. George Tsoumis in Science and Technology of Wood: Structure, Properties, Utilization describes the process of the combustion of wood. He states: “Wood burns under the action of high temperatures, which result in its chemical decomposition and production of flammable gases. Gradually the following changes take place:
a. Evaporation of moisture (up to 100°C/212°F)
b. Evaporation of volatile substances (95-150°C/203-302°F and higher)
c. Superficial carbonization and slow exit of flammable gases, followed by ignition and glow (150-200°C/302-392°F)
d. Faster exit of flammable gases, followed by ignition and glow (200-370°C/392-698°F)
e. Fast ignition of flammable gases and formation of glowing charcoal (370-500°C/698-932°F)⁴

The surface temperatures of all wooden members tested never rose above the point necessary to vaporize moisture, although sustained high temperatures between ambient and 212°F will undoubtedly reduce moisture content of the sample. Care should be taken, however, in the selection of a portable heat source that does not have exposed heating element surfaces that could cause the spontaneous ignition of wood material with which it may come in contact. As an additional precaution, I recommend that simple method be developed to extinguish a fire in the unlikely

event of contact between the heating element surface and a wooden member or
surrounding vegetation creating combustion.

This work will be continued in conjunction with a second research program
focused on the creation and testing of a risk assessment program for these structures
based on the identification and rating of a diverse variety of environmental and
resource related attributes. A second visit to Grand Canyon National Park in the
summer of 2012 will implement the methodology developed in this thesis to test and
establish a monitoring protocol for the Park Service to measure the rate of change
in specific conditions considered relevant for the preservation of wooden structures
in Grand Canyon National Park. Conclusions and recommendations derived from
the research conducted in this thesis will inform the development of a non-contact,
non-destructive methodology for monitoring changes in configuration and material
condition of natural wooden structures constructed by the Navajo and Havasupai
peoples located in Grand Canyon National Park.
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