INFRARED THERMOGRAPHY AS A NON-DESTRUCTIVE METHOD TO MEASURE MOISTURE PATTERNS IN LIME-PLASTER FINISHES OF HISTORIC FREE-STANDING EXTERIOR ADOBE WALLS

Namratha Reddy Kondam

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

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Program Chair
Frank G. Matero
Professor

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Table of Contents

List of Figures

All figures by the author, unless otherwise noted

List of Tables

All tables by the author, unless otherwise noted

Chapter 1: Introduction

This thesis studies the viability of in situ infrared thermography (IRT) to identify the presence of moisture in the lime-plastered adobe walls of Campo Santo at Tumacácori National Historical Park, a Spanish Colonial mission near Tucson, Arizona. I was first introduced to the site during my spring semester 2019 for the course HSPV 747-401 Conservation and Management of Archaeological Sites and Landscapes, where I worked on the structural analysis of the granary structure which shares a common wall with the Campo Santo. Later in summer 2019, I had an opportunity to work remotely on condition assessment drawings of the Campo Santo as a part of my summer internship at the Center for Architectural Conservation (CAC) of the Stuart Weitzman School of Design. To further understand the conditions of the Tumacácori Campo Santo structure and identify moisture issues, a non-destructive method: Infrared Thermography was tested in this thesis. The validity of the IRT method was tested by correlating the IRT findings with results of indirect and direct moisture monitoring methods such as capacitance moisture meters and gravimetric analysis.

The importance of this thesis was to provide a non-invasive moisture monitoring tool for the National Park Service staff at Tumacácori. The Campo Santo is a rare and significant character-defining feature of the mission complex, and its original plastered walls contain both decoration and historic graffiti unique to it alone. If valid, the IRT method of monitoring moisture would help the site stewards to visualize and indirectly measure moisture in the walls, enabling better diagnosis for the repair and maintenance of the historic structures.

The process for this thesis began with a brief review on adobe as a construction material with lime plaster in historic structures of the Southwestern region of the United States. Then the behavior, physical and mechanical properties exhibited by adobe structures when in contact with moisture were studied and analyzed for the Tumacácori site. Further, the physics of the moisture movement in an exterior free-standing adobe walls with lime plaster was described to understand the factors that might affect the IRT images.

Next IRT was reviewed as a tool for moisture mapping. The basic concept and physics involved in infrared thermography was defined followed by knowing the advantages, disadvantages, and limitations for this study. From various primary and secondary sources on IRT the factors that affect the thermal images and readings were identified.

After understanding the background and physics of lime plastered abode wall construction and IRT, soil and climate data of the Tumacácori Campo Santo site was collected and analyzed to understand their effects on the walls as well as the IRT method. Then the equipment required for IRT and indirect moisture monitoring method was finalized and shipped to the site for testing. The collected thermal images and indirect moisture and surface temperature readings were analyzed. Finally, conclusions and future recommendations were suggested on the use of IRT as a non-destructive method for identifying moisture.

Chapter 2. Adobe as a building material

2.1 Adobe walls and their components

Adobe brick is one of the oldest and most common of building materials. Many historic structures in the arid southwestern region of the United States were constructed with adobe as the principal building material. These include sun-dried mud bricks, soil mortar, and rammed and puddled earth.[1] Traditionally, adobe bricks were not kiln-fired. Because adobe bricks are not fired in a kiln, they do not develop the same hardness or compressive strength as kiln-fired brick. Therefore, they remain unstable by shrinking and swelling constantly with their changing water content.[2] The fluctuations of the water content in these bricks affect their shape and compressive strength.

Adobe bricks**:** Adobe bricks were made by mixing sand and clay (sometimes fine gravel) with water to a plastic consistency. Then straw or grass was added as a binder to help the bricks shrink uniformly while they dry.[3] The prepared mix was placed in wooden forms, tamped, and levelled by hand. The bricks were then "turned out" of the mold to dry on a level surface covered with straw or grass so that the bricks would not stick. After several days of drying, the adobe bricks were air-cured for 4 weeks or longer.[4]

Mortar: Historically, most adobe walls were composed of adobe bricks laid with mud mortar. Such mortar exhibited the same properties as the bricks: relatively weak and susceptible to the

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[1] James R. Clifton, *Preservation of Historic Adobe Structures – A Status Report*, (Washington: Dept. of Commerce, National Bureau of Standards, Institute for Applied Technology, 1977), Technical Note 934. http://hdl.handle.net/2027/mdp.39015086559831

[2] Technical Preservation Services, "Preservation of Historic Adobe Buildings, 1978", U.S. Department of the Interior National Park Service, last accessed May 6, 2021, https://www.nps.gov/tps/how-to-preserve/briefs/5-adobe-buildings.htm

[3] Ibid.

[4] Ibid.

same hygroscopic expansion and contraction, thermal expansion and contraction, and deterioration.[5]

Surface coatings: The adobe surfaces exposed to rain are prone to erosion and need frequent maintenance. Traditional surface coatings such as mud plaster, lime plaster, whitewash, and cementitious stucco protect the exterior and interior surfaces of adobe walls.[6] Periodic re-application of these sacrificial surface coatings to the adobe walls maintains their protection and appearance.

Plaster: Lime plaster, was widely used in the 19th-century as both an exterior and interior coating and was harder and more water resistant than mud plaster. The lime plaster was less flexible and cracked easily. It consists of lime, sand, and water and was applied in multiple coats. Traditionally adobe walls were often scored diagonally with hatchets, making grooves about 1-1/2 inches deep so that the lime plaster would anchor to the adobe. The grooves were filled with a mixture of lime mortar and stone chips or broken brick or roof tiles.[7] The walls were then covered with lime plaster approximately one to two inches thick.

To protect the walls from rainwater, 19th-century builders often capped the parapet walls with fired bricks. These bricks were harder and resisted the erosive action of rainwater. Projection of the cap beyond the face of the wall formed a drip edge which reduced the amount

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[5] Technical Preservation Services, "Preservation of Historic Adobe Buildings, 1978", U.S. Department of the Interior National Park Service, last accessed May 6, 2021, https://www.nps.gov/tps/how-to-preserve/briefs/5-adobe-buildings.htm
[6] Ibid.
[7] Ibid.

of water on the wall face. Traditional lime mortar with the fired brick was advised because it was more watertight and compatible with the harder brick.[8]

2.2 Deteriorating moisture processes in historic adobe walls with lime plaster finish

Moisture has the greatest effect on the adobe's performance and durability. In adobe structures, moisture wetting and drying can cause shrinkage cracks, erosion, undercutting at the base and under the top of coping, and loss of mechanical properties. All renders such as mud, lime, gypsum, or cement plasters are applied to protect the underlying adobe from direct moisture contact. Of these, mud or earthen renders are the most compatible with the adobe; however, like adobe they are also sensitive to moisture and are a sacrificial protection that requires frequent renewal. The other renders such as lime plasters are only as protective as they are continuous and in complete contact with adobe support. Deteriorations like cracking, coving, detachment, erosion and subflorescence of these renders often occur in the presence of moisture. Therefore, determining the source of moisture, amount of moisture, and water movement in adobe structures is an important aspect of their preservation.[9]

The main sources of moisture to enter an exterior wall structure are rainfall, soil moisture and ground water. Changes in soil moisture and ground water levels may be a result of a high-water table, seasonal water fluctuations, the presence of underground springs, improper

[8] Technical Preservation Services, "Preservation of Historic Adobe Buildings, 1978", U.S. Department of the Interior National Park Service, last accessed May 6, 2021, https://www.nps.gov/tps/how-to-preserve/briefs/5-adobe-buildings.htm

[9] James R. Clifton, *Preservation of Historic Adobe Structures – A Status Report*, (Washington: Dept. of Commerce, National Bureau of Standards, Institute for Applied Technology, 1977), Technical Note 934. http://hdl.handle.net/2027/mdp.39015086559831

drainage, excessive watering to plants, or grade changes on either side of the wall.[10] The adobe structures might have satisfactory durability in places where little or no rainfall occurs. Still, it is difficult to keep the adobe structure dry throughout the year. “Even in the arid southwestern region of the United States where the rainfall may be 6 inches (15 cm) or less it might be more harmful to adobe than a moderate rainfall as the total annual rainfall may take place in one or two severe rainstorms”.[11] Although lime plaster is permeable and allows evaporation of moisture from the surface of the wall, it is usually harder, denser, and less porous than the adobe beneath. Lime plaster deterioration is affected by the presence of moisture, but it expands or contracts less than the adobe bricks beneath the plaster thus causing detachment through shear forces. This difference in properties between adobe bricks and the lime plaster finish thus have consequences for, the transfer of moisture and rate of evaporation of the wall assembly.

In most cases, the deterioration processes directly or indirectly correlate with the presence of excess moisture. The various moisture-based processes of deterioration of adobe walls with lime plaster are (See Figures 2.1 and 2.2)

a) Action of rain water:

- Entering the fissures and cracks at the top of walls and in vertical lime plaster surfaces of walls

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[10] Technical Preservation Services, “Preservation of Historic Adobe Buildings, 1978”, U.S. Department of the Interior National Park Service, last accessed May 6, 2021, https://www.nps.gov/tps/how-to-preserve/briefs/5-adobe-buildings.htm
[11] Paul Wencil Brown and James R. Clifton, “Adobe I: The Properties of Adobe,” *Studies in Conservation* 23, no. 4 (November 1978): 139-146, https://www.jstor.org/stable/1505842

- Wind-blown rain water absorbed by the vertical lime plaster surface of the walls.
- Back splashing of rain water on the lime plaster at the base of the wall
- Undercutting at the base of walls due to accumulation of rain water

b) ***Weathering:*** Slow wind and rain erosion of the vertical lime plaster surfaces of walls and exposed adobe brick surfaces.

c) ***Action of ground water and soil moisture:*** Ground water and soil moisture rise through capillary action into the wall and can cause the adobe to swell, buckle the lime plaster, then cove. The presence of soluble salts can aggravate this action.

Out of all, the processes (a) and (c) cause much more damage than process (b).[12]

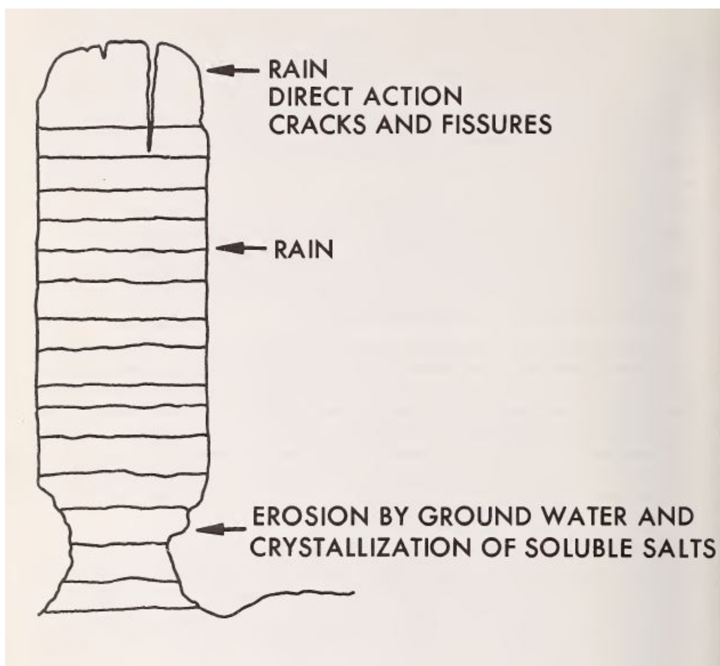
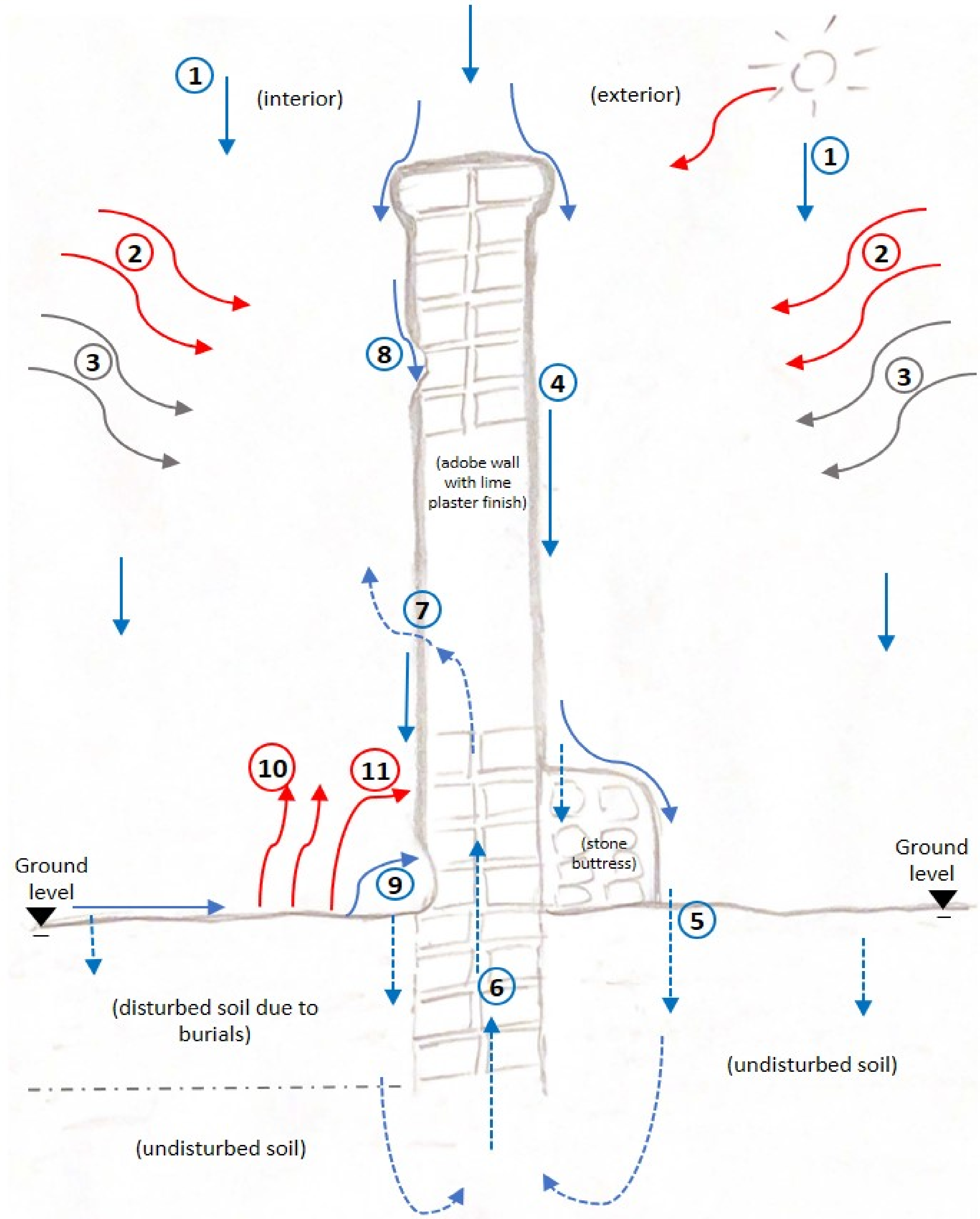


Figure 2.1: Deterioration action of water on adobe walls, from James R. Clifton, Preservation of Historic Adobe structures – A status report (U.S Department of commerce 1977)

[12] James R. Clifton, *Preservation of Historic Adobe Structures – A Status Report*, (Washington: Dept. of Commerce, National Bureau of Standards, Institute for Applied Technology, 1977), Technical Note 934. http://hdl.handle.net/2027/mdp.39015086559831



1. Rain
2. Heat from sun
3. Wind
4. Rain falling on wall
5. Water seeping into soil
6. Capillary rise of moisture
7. Moisture evaporated from lime-plaster surface
8. Water entering via wall defects
9. Back splashing of water at bottom
10. Emitted heat radiation from soil surface
11. Reflected heat radiation from soil surface onto the bottom of wall

Figure 2.2: Campo Santo wall section (adobe wall with lime plaster finish) hygrothermal interaction diagram

Rain water can saturate the lime plaster and adobe bricks directly through absorption through the plaster itself or by water entering via cracks, fissures, or other defects on the wall. Saturated bricks lose cohesive strength, especially at the base where they can cause deformation and out of plane alignment of the walls. Moisture entering the wall through plaster cracks can result in trapping of moisture within the wall system by preventing drying. If left unattended, rainwater can eventually damage and destroy the adobe walls, resulting in their continued deterioration and ultimate collapse. The back splashing of water at the base of the walls may cause "coving" (the hollowing-out of the wall just above grade level). Coving can also be caused by spalling of the lime plaster during the freeze-thaw cycles.

Lime plaster then can prevent the adobe from drying, increasing the moisture content within the adobe bricks compared to that of the lime plaster itself which is exposed to the external environment and drying. If a source of moisture is present for the lime plaster finished historic adobe walls, we can assume that the moisture content in the adobe bricks is greater than the moisture content of the lime plaster. Therefore, if we can identify the presence of moisture sources, the moisture patterns within the lime plaster surface might allow us to predict the presence of moisture in the adobe bricks beneath the lime plaster.

Most historic adobe structures do not have adequate waterproof foundations to prevent the rise of ground water or soil moisture by capillary action.[13] The moisture in the soil enters the wall structure below grade through capillary action. The moisture leaves the wall through evaporation to the surrounding dry air including voids in dry soil near the soil surface. Additionally, if the ground water or soil moisture has dissolved minerals or high salt content, the

[13] Paul Wencil Brown and James R. Clifton, "Adobe I: The Properties of Adobe," *Studies in Conservation* 23, no. 4 (November 1978): 139-146, https://www.jstor.org/stable/1505842

salts may be deposited behind the lime plaster surface of the adobe walls when the water evaporates from the lime plaster. If the evaporation occurs within the lime plaster, the subflorescence will occur there. Minerals and salt crystals formed within the adobe or plaster can result in the spalling of the surface.[14]

The deteriorating processes typically take place in cycles of repeated action such as frequent shrink-swell cycles and frequent freeze-thaw cycles. The adobe wall shrinks and swells due to the drying and wetting processes, resulting in their cracking. If the wet and dry cycles continue over a period of time, the size of the cracks and extent of cracking can endanger the wall's structural integrity. Furthermore, excessive moisture combined with the frequent freeze-thaw cycles can result in more damage.

[14] James R. Clifton and Frankie L. Davis, *Protecting Adobe Walls from Ground Water*, (Washington: Dept. of Commerce, National Bureau of Standards, Institute for Applied Technology, 1979), Technical Note 996.

Chapter 3: Infrared Thermography (IRT)

3.1 Infrared Thermography as a tool for moisture mapping

Studies support the role of IRT as a predictive monitoring method for maintenance as it allows the mapping of risk areas to perform early detection of factors that may be responsible for future damage when the extent of deterioration is not yet visible.[15] IRT is a method that detects infrared energy emitted from, transferred through, and reflected by, an object's surface, converts the reading to surface temperature, and displays surface temperature distribution (Figure 3.1). If the reflected and transmitted thermal energy are small compared to the emitted thermal energy, the indicated surface temperature approximates the true surface temperature. The sensitivity of the infrared camera can detect small differences in surface temperatures within the camera view and provide a colorized image of the temperature variation (Figure 3.2).

There are two approaches to obtain a thermal gradient of sufficient range to generate a meaningful thermal image – the passive and active methods. In the passive approach, thermal energy to heat the structure is typically obtained from exposure by solar (sun) radiation or from transmitted thermal energy from inside the building on a cold day. The active approach in IRT involves the application of a controlled amount of heating on or through a structure.

[15] Elisabetta Rosina and Jonathan Spodek, "Using Infrared Thermography to Detect Moisture in Historic Masonry: A Case Study in Indiana," *APT Bulletin: The Journal of Preservation Technology* 34, no. 1 (2003): 11-16, https://www.jstor.org/stable/1504847

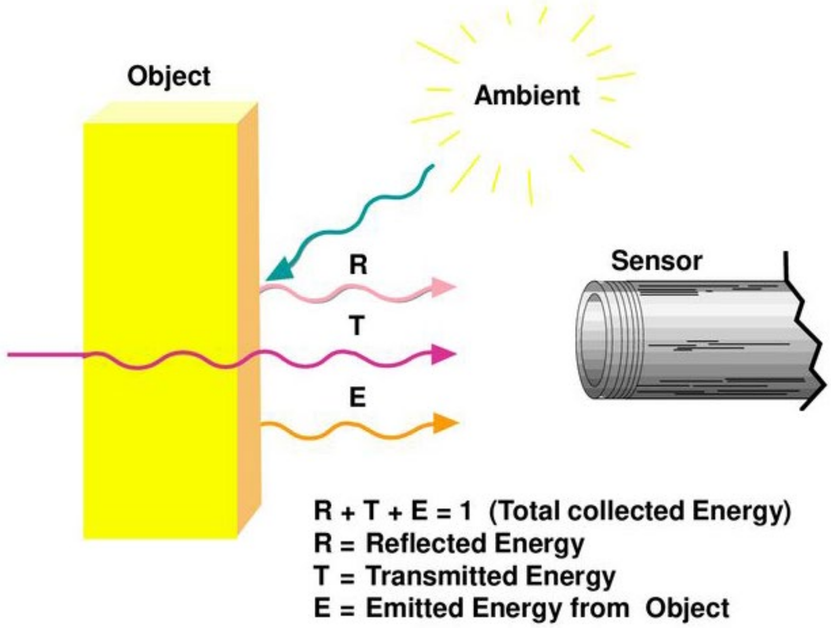


Figure 3.1: A thermal imagining camera senses incident energy (R + T + E) from an object, courtesy of SlidePlayer website, https://slideplayer.com/slide/13788979/

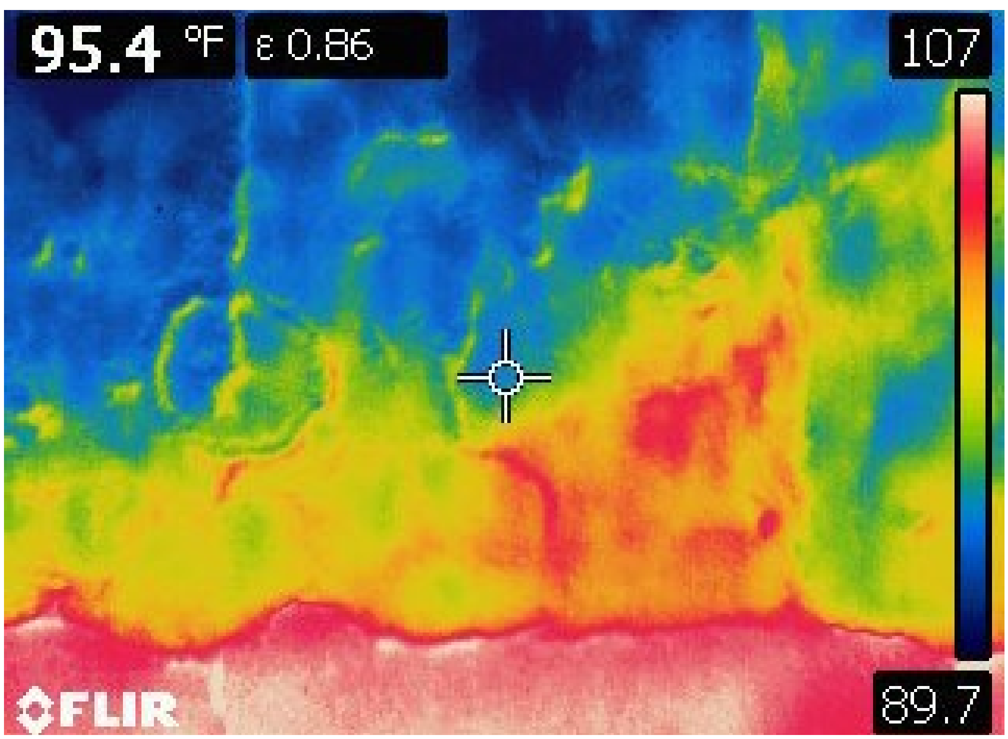


Figure 3.2: A thermal (colorized) image of a wall surface taken from an infrared camera

3.2 Relationship between temperature and moisture content in porous materials

Standardized procedures such as ASTM methods are currently not available to detect moisture in building components using IRT, or to establish a relationship between moisture content to differences in temperature. The surface temperature recorded by the passive IRT approach, can help identify and locate anomalous moisture content or changes in porosity by indicating the abnormal temperature patterns on the surface.[16] Moisture content changes are related to surface temperature changes and can, therefore, be detected by an IRT, due to three physical phenomena:

- Evaporative cooling at the moist area
- Increased heat storage capacity of the moist material
- Reduced thermal resistance of the moist material.[17]

Moisture influences how building materials respond to temperature fluctuations due to thermal inertia and evaporation, and many other reasons can cause surface temperature differences within the wall assembly.[18] Thermal imagining is also useful where the moisture content has no clear relation to external moisture sources or does not correspond with capillary action from the subsoil.[19] For this thesis, out of all these phenomena, evaporative cooling and heat retention were considered to provide sufficient emitted infrared radiation as possible

[16] Ermanno Grinzato et al., "Infrared Thermography for Moisture Detection: A Laboratory Study and In-situ Test," *Materials Evaluation* (January 2011): 97-104, https://www.researchgate.net/publication/236255934

[17] Eva Barreira and Ricardo M.S. F Almedia, *Infrared Thermography for Building Moisture Inspection,* Springer Briefs in Applied Sciences and Technology, (Switzerland: Springer 2019), https://doi.org/10.1007/978-3-319-75386-7

[18] Lew Harriman, "Moisture Investigations Using Thermal Cameras," *Journal of National Institute of Building Sciences* (February 2014): 12-14

[19] Lukáš Balík et al., "Application of infrared thermography in complex moisture inspection of the Schebek Palace," *API Conference Proceedings* 1866, Thermophysics (2017), https://doi.org/10.1063/1.4994482

indications of moisture content when conditions are favorable. In the case of a free-standing exterior wall, transmitted thermal energy is likely to be small when the IRT image is taken on the side of the wall with solar radiation, and might be important when the IRT image is taken on the side of the wall opposite solar radiation.

"Although research is ongoing, current IRT procedures do not easily supply quantitative data on the water content; therefore, only the qualitative approach can be applied extensively."[20] So, knowledge of building physics such as the flows of moisture and thermal energy is necessary to correctly interpret the thermal image. Building physics enables us to establish the moisture sources, storage, and sinks, the moisture paths and modes of transport and to identify the coincident thermal flows. To study the IRT quantitatively, we need a clear relationship between movement of thermal energy and moisture. Interpretation of IRT images might be incorrect because "the temperature of damp areas may be lower than that of dryer areas due to surface evaporation, or the temperature may be higher due to higher thermal inertia of water compared to the dry building materials."[21]

Moisture issues can be identified through visual analysis, gravimetric analysis, and in-situ testing such as using capacitance moisture meters and infrared thermography. The accurate way to quantify moisture content and movement is to integrate IRT with other direct moisture content methods such as gravimetric analysis. The gravimetric tests can then be used to interpret indirect moisture measurements, such as electrical conductance or capacitance

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[20] Jonathan Spodek and Elisabetta Rosina, "Application of Infrared Thermography to Historic Building Investigation," *Journal of Architectural Conservation* 15:1 (March 2009): 65-81, https://doi.org/10.1080/13556207.2009.10785040

[21] Ermanno Grinzato et al., "Infrared Thermography for Moisture Detection: A Laboratory Study and In-situ Test," *Materials Evaluation* (January 2011): 97-104, https://www.researchgate.net/publication/236255934

measurements in the field at the time of the IRT image. Thermal imaging is a useful tool but must be accompanied and supported by other direct and indirect moisture content and temperature readings of the context of the building under study to give robust conclusions.[22] The moisture readings obtained from the indirect methods help clarify the thermal images and support conclusions with greater certainty and clarity. For this thesis, only non-destructive moisture measurement methods were allowed. A capacitance moisture meter was utilized as an appropriate indirect measurement method as it allowed identification of wall moisture in larger areas.[23] "The quantitative tests are sometimes unreliable, and reliability is critical in the field of cultural heritage preservation because the moisture content assessment is crucial."[24] Additional testing under varied weather conditions and different times of the year can help determine conditions in which moisture content is highest and identify the different sources of moisture.[25] For example, whether a wall is damp due to permanent groundwater versus poor surface drainage.

3.3 Factors affecting the infrared images and readings

In passive IRT, the building orientation and relationships to adjacent structures, trees or buildings that affect thermal energy by casting shadows are crucial. As buildings are subjected to slow and varying boundary conditions for both moisture and thermal energy, determining the correct time to perform testing and its duration is critical. When using IRT, it is important to

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[22] Lew Harriman, "Moisture Investigations Using Thermal Cameras," *Journal of National Institute of Building Sciences* (February 2014): 12-14
[23] Lukáš Balík et al., "Application of infrared thermography in complex moisture inspection of the Schebek Palace," *API Conference Proceedings* 1866, Thermophysics (2017), https://doi.org/10.1063/1.4994482
[24] Ibid.
[25] Elisabetta Rosina and Jonathan Spodek, "Using Infrared Thermography to Detect Moisture in Historic Masonry: A Case Study in Indiana," *APT Bulletin: The Journal of Preservation Technology* 34, no. 1 (2003): 11-16, https://www.jstor.org/stable/1504847

account for several material properties to interpret the thermal images properly. Some of them are the color (darker colors absorb more heat than lighter colors), material density, material continuity (voids or detachment of layers will affect hygrothermal transfer), and porosity (affect thermal inertia), and the emissivity (which should be mentioned specifically when discussing the parameters affecting the measurement of temperature). Surface temperature occurring due to evaporation depends on the air temperature, the relative humidity levels, air movement, and direct solar radiation.[26]

Therefore, documentation of the time of day, air temperature, wind speed, current and past precipitation and weather conditions, and the face of the building undergoing thermal imaging, is very important while performing an IRT testing.

[26] Jonathan Spodek and Elisabetta Rosina, "Application of Infrared Thermography to Historic Building Investigation," *Journal of Architectural Conservation* 15:1 (March 2009): 65-81, https://doi.org/10.1080/13556207.2009.10785040

Chapter 4: Campo Santo, Tumacácori National Historical Park, AZ

For the purpose of this thesis, the Campo Santo of the San José de Tumacácori mission in Arizona provided the test site.

4.1 History and timeline

The San José de Tumacácori mission located in Santa Cruz County, Arizona was originally established by Jesuit Father Kino in 1697, and the Franciscan Mission itself was built in late 18th century. This mission is now a preserved ruin as Tumacácori National Historical Park. Apart from the church, the mission encompasses other structures such as the Jesuit church footprint, convento footprint, convento complex, granary, cemetery (Campo Santo), mortuary chapel and lime kilns. In addition to the construction of the church, by 1822, the walled cemetery was completed. The Tumacácori cemetery, traditionally called Campo Santo, is towards the north end of the Church complex. Although information has been gathered and published on the construction, history, and continued conservation for the Mission Church, the Campo Santo does not appear to have had the same level of scholarly interest or documentation (See Appendix A and B).

4.2 Campo Santo: Structure description

The Campo Santo is about 176 feet long and 61 feet wide. It is surrounded on the west, north and part of the east sides by a wall 2 feet thick and about 7 to 8 feet high. Part of the east and the greater part of the south sides are taken up by buildings, such as the granary and rear of the church, respectively. Within the grounds of the Campo Santo in the southern end is a roofless circular structure known as the Mortuary Chapel, approximately 16 feet interior in diameter with a single doorway opening to the west. It is evident that the roof of the mortuary chapel was intended to be a dome, but the work was never completed. A gateway in the west wall provides entrance from outside to the cemetery. There are fourteen niches placed along the inner walls which once provided a place for the Stations of the Cross, a feature common in Catholic colonial cemeteries. It is not known if any statues or other items were ever placed in them. It is possible that the crosses carved into the walls in various places may have been markers for grave sites. The graffiti is over fifty years old and is now protected.[27]

Frank Pinkley, in his 1921 report on the Mission described the Campo Santo walls "made of unburned adobe bricks and covered inside and out with two coats of lime plaster. The outside of the wall was decorated in a dot pattern with fragments of slag and bricks in the same manner as the lower wall of the church. The inside was finished with a plain coat of hard plaster."[28] Both finishes are still extant on much of the walls and are a major character defining feature of the Campo Santo. For the mortuary chapel, only the first coat of plaster was put on the interior walls, but no traces of the second or finishing coat of plaster appears to have been applied to the exterior. Instead, a single coat of plaster has been applied with fragments of crushed brick probably to provide keys for the final finish layer that was never applied.[29]

Throughout history various repair campaigns were performed on different sections of the Campo Santo walls (See Appendix B). Plastering and patchwork repairs were done to stabilize the lime plastered adobe walls. Each re-application of plaster and surface coating campaign used different recipes of plastering materials and coatings, whose design mix details

[27] Ruby Edwards, "Tumacácori Cemetery," *Tumacácori National Historical Park Volunteer Handbook*, February 27, 1999
[28] Frank Pinkley, "Report on Tumacácori Mission," *Tumacácori National Monuments*, (National park Service, 1921)
[29] Ibid.

are unknown. This has resulted in non-uniform color and material properties of the finish plaster surface of the Campo Santo walls.

4.3 Soil, topography and climate around the site

The Pima series of soils lie beneath Tumacácori mission church site. Pima soils are well-drained soils formed in stream alluvium with low runoff. These soils are on alluvial fans and flood plains and have slopes of 0 to 3 percent.[30] The Pima soils are slightly to moderately alkaline (See Appendix C). Pima soil can be silty loam, silty clay loam, loam, clay loam, and fine sandy loam depending on the particle size distribution of clay and sand. Usually, particle size control section averages more than 18 percent clay and less than 15 percent sand coarser than very fine sand.[31] The Campo Santo is a burial ground filled with human remains beneath the ground. So, there is high chance of salts present within the soil due to the decomposition of human remains.[32]

The site is situated at a latitude of 32.22189 N and longitude of 110.92624 W with an elevation of approximately 3,279 feet. The Campo Santo area lies in a low-lying valley with a fairly flat terrain, and the terrain slowly slopes up (an increase of elevation) as we go the west side where the Tumacácori peak is situated (See Appendix C).

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[30] Soil data is obtained from an Interactive map which allows to explore USDA-NCSS soil survey data throughout most U.S. Developed by the California Soil Resource Lab at UC Davis and UC-ANR in collaboration with the USDA Natural Resources Conservation Service, https://casoilresource.lawr.ucdavis.edu/gmap/

[31] The information of Pima soil series is referred from the interactive map Soil data explorer, https://casoilresource.lawr.ucdavis.edu/sde/?series=pima

[32] B.B. Dent, S.L. Forbes and B.H. Stuart, "Review of human decomposition processes in soil," *Environmental Geology* 45 (2004):576–585, https://doi.org/10.1007/s00254-003-0913-z

The climate of Tumacácori, is hot and partly cloudy in summers, and the winters are cold, dry, and mostly clear. Over the course of the year, the temperature typically varies from 38°F to 97°F and is rarely below 28°F or above 103°F.[33] The hottest months are from end of May to September and the coolest months are from November to early March. The Tumacácori site receives the highest precipitation in July and August, and some precipitation from November to February (See Appendix C).

The Mission San José de Tumacácori is a part of the Sonoran Desert I&M (NPS Inventory and Monitoring Program) network. This network was characterized as having mild winters and hot summers, with year-round high diurnal temperature swings. It is typically free of frosts but has an intense monsoon season in July and August.[34] According to the 30-year summary of measured data from 1981 to 2010, the hottest month at Tumacácori was June with an average maximum daily temperature of 96.8 °F (36 °C) and the temperature often exceeded 105 °F (40 °C) during the hottest time. Daily temperature swings between day and night could be as great as 59 °F (15 °C) or more.[35] The recent climate change pattern show the possibility of extreme precipitation events which could have serious consequences on the adobe walls and its finishes.

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[33] Weather Spark, "Average Weather in Tubac Arizona," last accessed April 2021, https://weatherspark.com/y/2584/Average-Weather-in-Tubac-Arizona-United-States-Year-Round

[34] Davey, C.A., K.T. Redmond, and D.B. Simeral. "Weather and Climate Inventory," National Park Service, Sonoran Desert Network, Natural Resource Technical Report NPS/SODN/NRTR (June 2007) Fort Collins, Colorado

[35] Ibid.

Chapter 5: Laboratory testing and results

5.1 Laboratory testing

Lime plaster and adobe brick samples of the Campo Santo walls were collected and shipped to the University of Pennsylvania laboratories in March 2021 (Figures 5.1 and 5.2). Samples were collected by Alex Lim of Tumacácori National Park Services (NPS), from the west-facing east interior Campo Santo wall section which resemble the majority of the Campo Santo walls. The following quantities are measured using ASTM standard procedures (Tables 5.1 and 5.2).

Figure 5.1: Lime plaster samples from Campo Santo walls at Tumacácori

Table 5.1: Quantities to be measured and the procedure followed for lime plaster samples

Quantity to be measured	Procedure and Standards referred
Visual analysis	ASTM D1535-12a Standard Practice for Specifying Color by the Munsell System
Porosity	ASTM C97-96 Standard Test Methods for Absorption and Bulk Specific Gravity of Dimension Stone
Presence of salts	Semi-quantitative salt analysis.[36].

Figure 5.2: Adobe bricks fragments from Campo Santo walls at Tumacácori

[36] Casey Alane Weisdock, "Performance-Based Evaluation of Salt Crystallization Inhibitors as a Means to Mitigate Salt Damage in Terracotta," *Theses Historic Preservation*, (2016), Paper 604, http://repository.upenn.edu/hp_theses/604

Table 5.2: Quantities to be measured and the procedure followed for adobe brick samples

Quantity to be measured	**Procedure and Standards referred**
Visual analysis	ASTM D1535-12a Standard Practice for Specifying Color by the Munsell System
Porosity	Liquid nitrogen test, based on ASTM C830 Standard Test Methods for Apparent Porosity, Liquid Absorption, Apparent Specific Gravity, and Bulk Density of Refractory Shapes by Vacuum Pressure. Procedure referred from Matteini, Irene 2014 thesis.[37] and 1979 Report which includes Tumacácori mission church adobe and soil samples analysis.[38]
Presence of salts	Semi-quantitative salt analysis.[39]
Particle size distribution	ASTM C136-06 Standard Method for Sieve Analysis of Fine and Coarse Aggregates. ASTM STP 447 B Manual on Test Sieving Methods

[37] Irene Matteini, "An Assessment and Evaluation of Acidic Cleaning Methods on Unglazed Terracotta Using Accelerated Weathering Test Protocols", *Theses Historic Preservation*, (2014), Paper 574, http://repository.upenn.edu/hp_theses/574

[38] Paul Wencil Brown, Carl R. Robbins and James R. Clifton, "Adobe II: Factors affecting the durability of adobe structures," *Studies in Conservation* 24, no. 1 (February 1979): 23-39, https://www.jstor.org/stable/1505920

[39] Casey Alane Weisdock, "Performance-Based Evaluation of Salt Crystallization Inhibitors as a Means to Mitigate Salt Damage in Terracotta," *Theses Historic Preservation*, (2016), Paper 604, http://repository.upenn.edu/hp_theses/604

5.2 Laboratory results

5.2.1 Lime plaster samples

Four lime plaster samples from the Campo Santo walls were collected by Alex Lim. First the plaster samples were cleaned from any adobe remains on the interior surface. Then six samples of roughly 2-inch cubes were prepared from the collected samples for the porosity tests (Figure 5.3). The porosity of all the six samples were measured using two methods: Indirect measurement through water absorption and hydrostatic weighing.

Figure 5.3: Two-inch cube lime plaster sample prepared for porosity measurement

General observations and visual analysis

All the lime plaster samples of Tumacácori Campo Santo had an overall off-white color (Munsell notation: WHITE 9.5/N). The samples were composed of two layers measuring approximately 1 inch thick each, with fragments of crushed brick embedded between the layers, probably added as a mechanical key between layers (Figure 5.4). The finish plaster exterior surface (Munsell notation: light brown 7.5 YR 6/4) was eroded and some samples had evidence of bio growth (Munsell notation: Grayish green 5GY 5/2) . The interior plaster surface had remains of adobe mortar which was cleaned before performing the experiments.

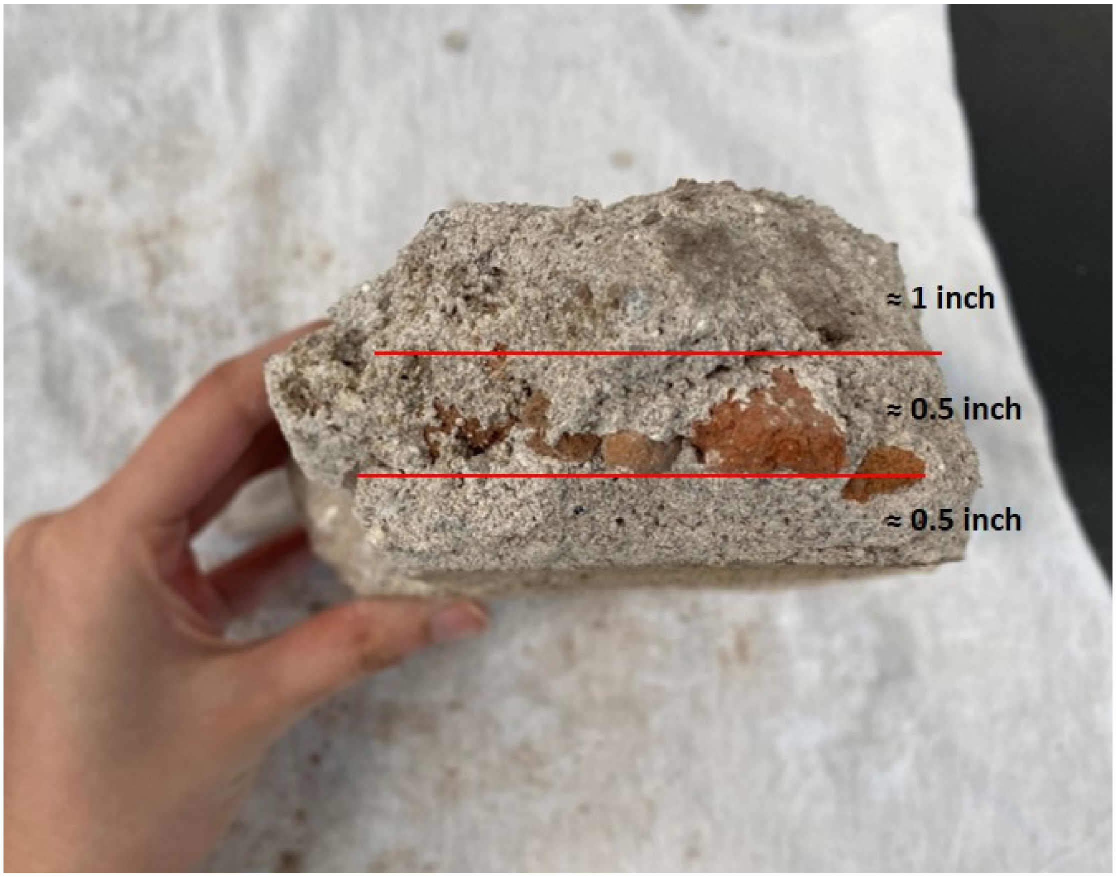

Figure 5.4: The two layers of lime plaster with embedded crushed brick fragments

Porosity measurement

The porosity of the lime plaster ranged from 27% to 29% based on indirect water absorption method and 27% to 31% based on hydrostatic weighing method. Therefore, the porosity of the lime plaster surface of Campo Santo walls ranged from 27% to 31% (See Appendix D, Table D.1 to D.4, Figures D.1 to D.3)

5.2.2 Adobe samples

Four adobe brick samples from the Campo Santo walls were collected by Alex Lim of NPS. Sieve analysis was performed on three of these samples and salt testing was performed on all four samples. Due to unavailability of equipment required for liquid nitrogen porosity test, a range of adobe porosity values were taken from a study done on adobe samples of Tumacácori Mission Church in 1979.[40] The 1979 study included size fraction analysis of adobe specimens taken from the Church interior and exterior walls along with exterior the soil samples taken from northeast corner of the grounds.

General observations and visual analysis

All the adobe samples of Tumacácori Campo Santo were brown (Munsell notation: varied between 7.5 YR 4/3 and 7.5 YR 4/2). These adobe samples had fine as well as coarse pores. Organic matter such as straw and twigs were also observed in the adobe matrix of these samples **(See figure 5.5).** Based on the 1979 study it was concluded that these organic fragments were added intentionally into the adobe mix. Also, "the Tumacácori site soil sample, was found to be high in silt and clay compared to the Tumacácori mission church wall adobe sample, suggesting that the coarser fractions were intentionally added to adobe mix to achieve the desired proportioning."[41] (see Appendix D, Table D.2)

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[40] Paul Wencil Brown, Carl R. Robbins and James R. Clifton, "Adobe II: Factors affecting the durability of adobe structures," *Studies in Conservation* 24, no. 1 (February 1979): 23-39, https://www.jstor.org/stable/1505920

[41] Ibid.

Figure 5.5: Adobe samples showing the organic matter (straw and twigs), gravel particles and pores

Particle size distribution and porosity measurement

The sieve analysis results of Tumacácori church adobe samples from 1979 were similar to our current sieve analysis results of Tumacácori's Campo Santo adobe samples (see Appendix D, Figures D.4 to D.8, Tables D.5 to D.7). Therefore, we assumed that our Campo Santo adobe samples porosity could be similar to the porosity values found in 1979 study (Table 5.3). Based on 1979 results the porosity of the adobe samples ranged from 34% to 43%, which, as expected, was more than that of the porosity of the lime plaster samples.

Based on the porosity values of both adobe and lime plaster samples, we assumed that the moisture content present in the interior adobe could be greater than that of the surface lime plaster finish.

Table 5.3: Table for porosities of Tumacácori Church adobe sample, from *Brown et al., Adobe II: Factors affecting the durability of adobe structures*, (February 1979): Table 8, Page 35

DENSITIES AND POROSITIES OF SELECTED ADOBE SAMPLES

Sample designation	*Density g/cc*	*Net pore volume cc/g*	*Average pore diameter* μm	*Measured total porosity** %
To_{10}	2·56	0·233	4·2	37·4
To_{11}	2·56	0·213	14·0	34·5
To_{12}	2·60	0·199	2·5	33·9
To_{17}	2·46	0·318	4·8	43·0
Fort Bowie	2·68	0·150	3·4	27·9
Escalante	2·80	0·227	2·8	38·2

*Size range 177–0·0035 μm.

5.2.3 Soluble salt analysis

Two lime plaster samples and four adobe samples from the Tumacácori Campo Santo walls were used for testing the presence of chlorides, sulphates, nitrites and nitrates. Twenty grams of each ground sample was passed through a no. 3 mesh and was mixed with 500ml of deionized water. This solution was agitated on a mechanical hot plate using a magnetic stir bar for 30 minutes to encourage the soluble salts in the adobe to dissolve. Three different EM Quant Strips were used for identifying the presence of salts: chlorides, sulphates, and nitrites/ nitrates (Figure 5.6). First all three strips were tested in plain deionized water to check the presence of any salts in the water. After each solution was agitated, all three EM Quant strips were inserted directly into the solution for 5-10 seconds. Then strips were removed and allowed to dry. The color change on the salt testing strips was compared with the color standards provided with the testing strips.

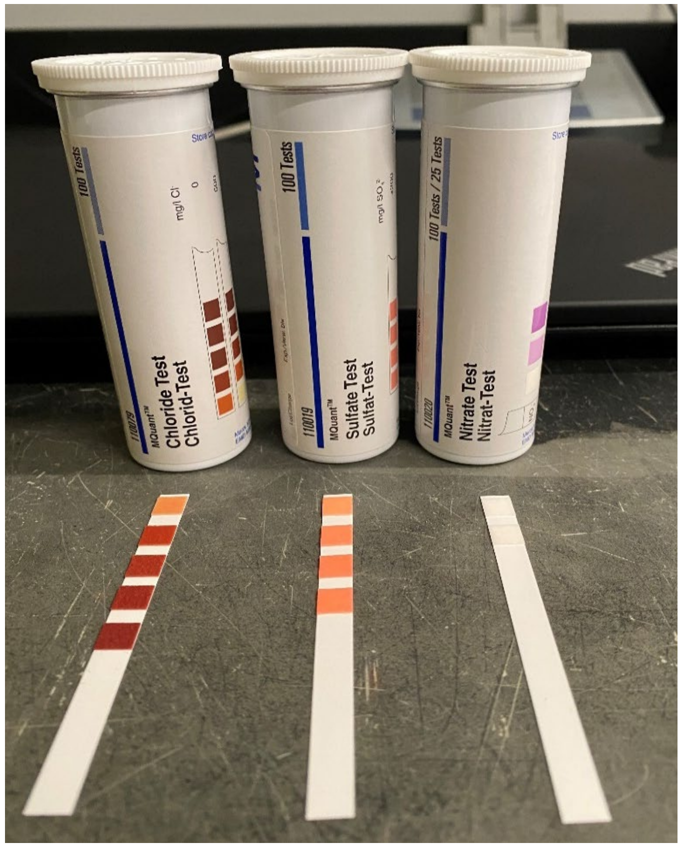

Figure 5.6: EM Quant Strips for chlorides, sulphates, and nitrites/ nitrates test

The results showed that there was no change in chloride and sulphate testing strips for all the six solution samples. But a color change was observed for the nitrites/ nitrates testing strips for four out of the six samples (Figures 5.7, 5.8 and 5.9, Table 5.4).

Table 5.4: Salt testing results of adobe and lime plaster samples

Salt testing							
		Adobe Samples				**Lime plaster samples**	
Testing strips	**Deionized water**	**S1**	**S2**	**S3**	**S4**	**P1**	**P2**
Chloride Cl^-	×	×	×	×	×	×	×
Sulphate SO_4^{-2}	×	×	×	×	×	×	×
Nitrite & Nitrate NO_2^-/ NO_3^-	×	Indicates presence of NO_2^- & NO_3^-	×	Indicates slight presence of NO_2^-	Indicates the presence of NO_2^-	×	Indicates slight presence of NO_2^- & NO_3^-

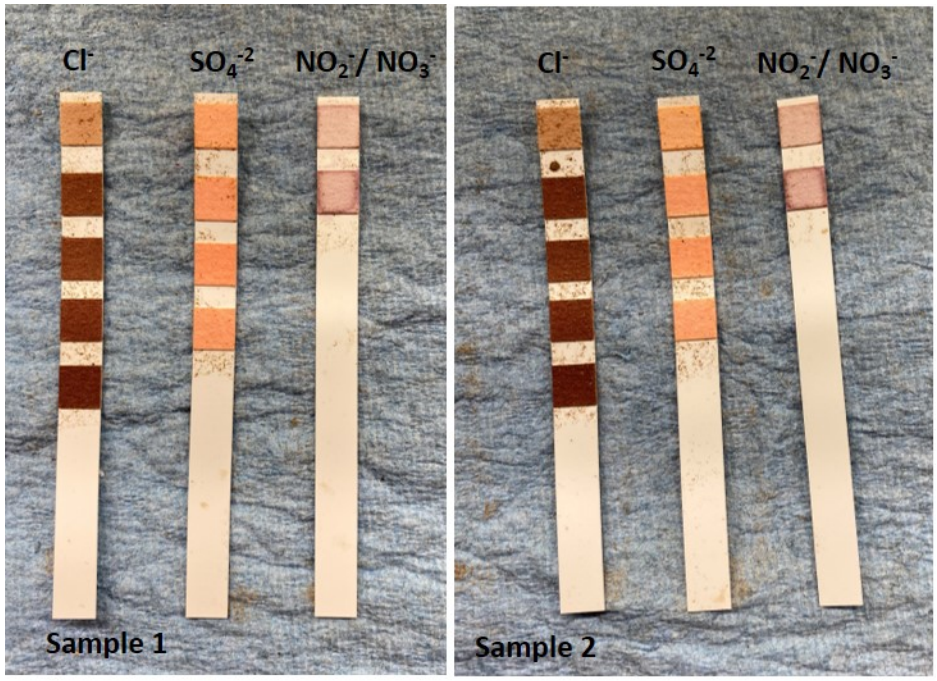

Figure 5.7: Salt strip results of Adobe samples 1 and 2

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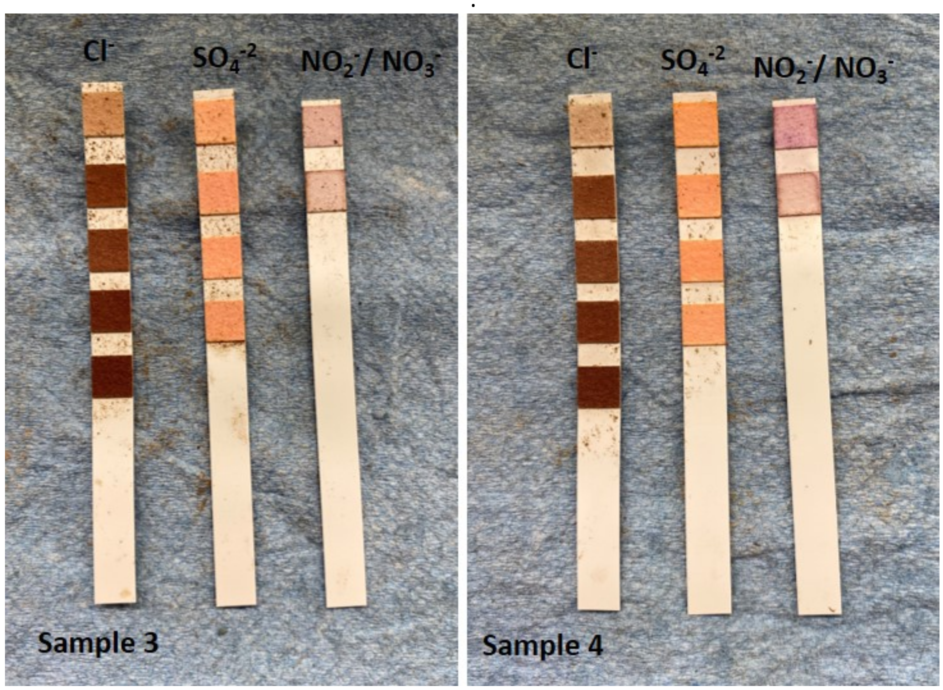

Figure 5.8: Salt strip results of Adobe samples 3 and 4

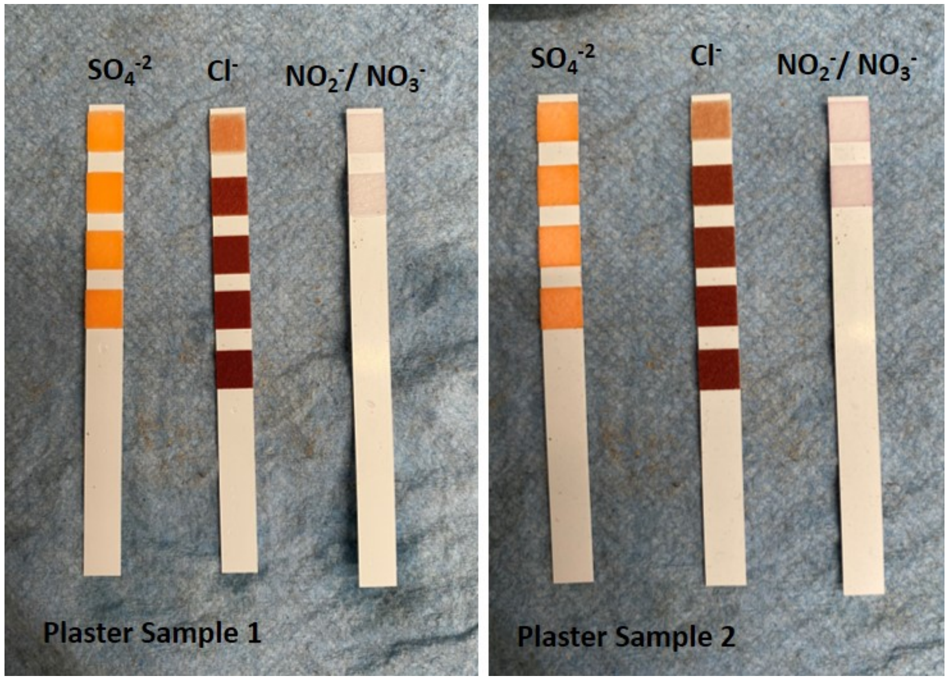

Figure 5.9: Salt strip results of lime plaster samples 1 and 2

During the decomposition process of human remains, “the ammonia produced may in turn be used by higher plants or various microbes, may be converted to nitrate, may accumulate in the soil or move through the groundwater system.”[42] In our case, the Campo Santo walls surround the burial ground filled with decomposing human remains. The presence of nitrites/ nitrates in the adobe bricks and lime plaster samples might have come from the ground water.

[42] B.B. Dent, S.L. Forbes and B.H. Stuart, “Review of human decomposition processes in soil,” *Environmental Geology* 45 (2004):576–585, https://doi.org/10.1007/s00254-003-0913-z

Chapter 6: Equipment and pre-site work

6.1 Primary equipment for thermal images and moisture readings of the Campo Santo walls

To validate and analyze infrared thermography method for identifying moisture in lime plaster of historic adobe walls, site testing and experiments were conducted. The FLIR E60 thermal camera was used in this thesis to take the thermal images of the Campo Santo wall sections. For the indirect measurement of moisture and temperature of the wall surfaces and soil at the base of the wall section, the Protimeter MMS2 Pinless moisture meter and FieldScout TDR 150 Soil moisture meters were used (Figures 6.1, 6.2 and see Appendix E).

Figure 6.1: (left) FLIR E60 thermal camera, (right) Protimeter MMS2 moisture meter, courtesy of google images

Figure 6.2: Fieldscout TDR 150 soil moisture meter, courtesy of google images

6.2 Wall section selection criteria

After selecting the instruments and equipment required for site work, three wall sections of approximately twenty feet in length and approximately six to seven feet high were selected as the testing sample in this research. For each wall section, thermal images, moisture and surface temperature readings were taken. The criteria assumed for selecting the sample wall sections depended not only on the material properties and conditions of the walls but also the site’s weather conditions. For this research the criteria considered was based on the type of material, plaster condition, the orientation of the wall, the direction of the wind and rainfall, and solar radiation (Figure 6.3). The three selected wall sections were:

1. One section of south-facing north (interior) wall near the north-west corner of the Campo Santo (Figure 6.4).

2. Two sections of east-facing west (interior) wall: Where one section is towards the south, near the west wall doorway whereas the other section is towards the north end of the west wall (Figures 6.5 and 6.6).

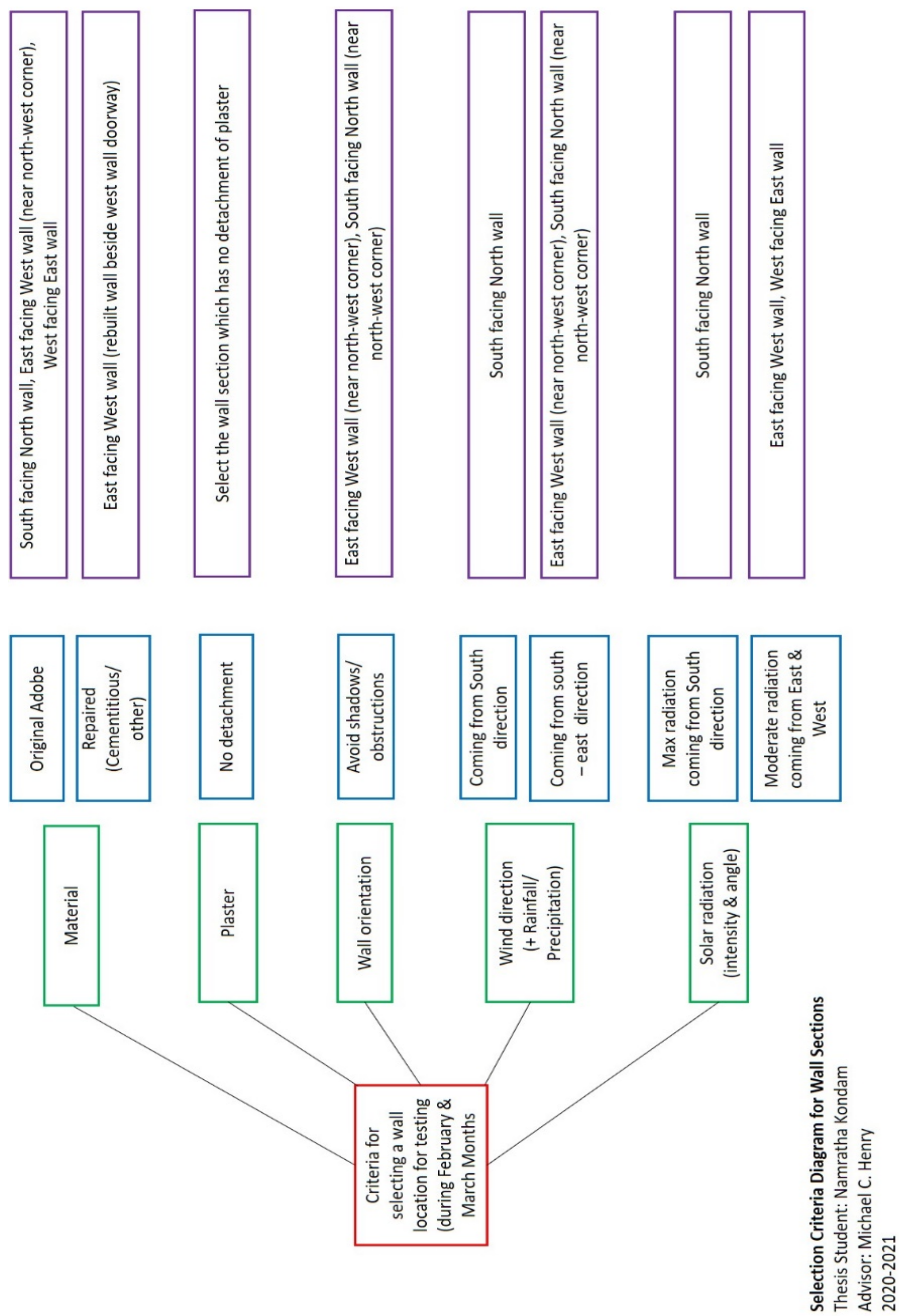

Figure 6.3: Selection Criteria Diagram for wall sections

Figure 6.4: Selected 20 *ft* wall section of south facing north wall with predominately original plaster

Figure 6.5: Selected 20 *ft* wall section of east facing west wall towards the north end with predominately original plaster

Figure 6.6: Selected 20 ft wall section of east facing west wall towards the south end with new plaster

6.3 Potential factors affecting the thermal image

Identifying the potential factors that affect the thermal images was important to get accurate readings. Based on the literature review and case studies on infrared thermography for in-situ testing, a list of external factors affecting the thermal images was prepared. For this research, the major external factors that might influence the thermal images were:

1. ***The temperature of the soil at the base of the wall:*** If the temperature of the soil was lower than the temperature of the wall then the thermal gradient of the wall section would be affected by the cooler or low temperatures at the base of the wall. If the temperature of the soil surface was higher than the wall, then the heat radiation can

bounce onto to lower part of the wall, resulting in higher temperature at the base of the wall.

2. ***Soil moisture around the wall:*** If the soil's moisture content was relatively high, then there was a possibility of more moisture within the walls.

3. ***Atmospheric conditions, direction and intensity of solar radiation:*** If the atmosphere around the wall had a low relative humidity and high wall temperature, then the images' thermal gradient would be affected by the evaporative cooling phenomenon.

Based on these factors and their variations with respect to time, a decision tree (Figure 6.7) was prepared to identify the optimum conditions to take the thermal images and minimize the adverse effects of these factors on the thermal results.

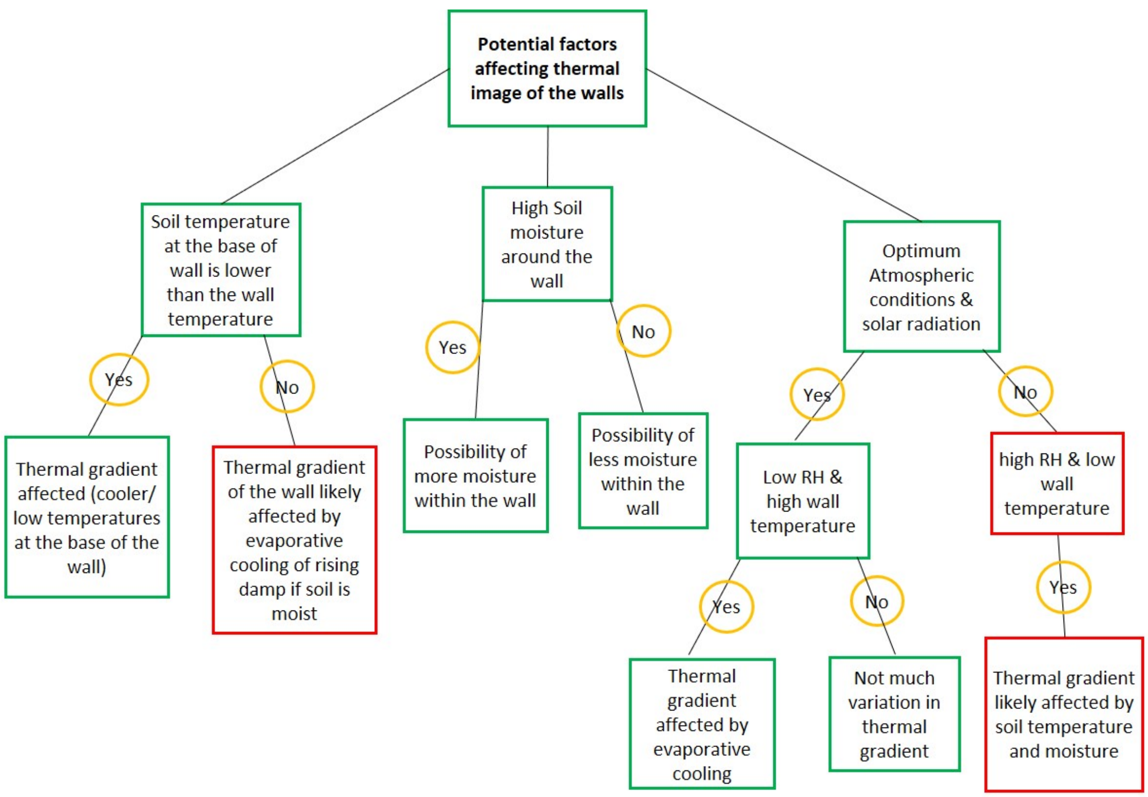

Figure 6.7: Decision tree for identifying the potential factors effecting the thermal images

6.4 Optimum conditions to take thermal images

Harriman's article on "Moisture Investigations using Thermal cameras" [43] and the case study on Infrared thermography [44] were used as a guidance for identifying the optimum conditions and timings to take thermal images. Due to time constraints, the IRT survey for this thesis was performed during late winter/ early spring season and the climatic conditions during this period of the year were not optimal for IRT. In this thesis two approaches were used to identify the optimum timings in a day to take the IRT images:

1. Analysis of the weather/ climate data of the site from previous years, mainly during the February and March months (Table 6.1).
2. Preliminary surveys conducted on site (in March 2021) to monitor the air and wall temperature, relative humidity of the air, direction and duration of solar radiation falling on each wall section.

Table 6.1: Overview of Tumacácori climate data from previous years

Condition	Analyzed data from previous years
Relative humidity (RH)	**Lowest RH** is from around **2pm to 5pm**, After 5pm the RH increases till midnight, remains high till morning and slowly drops by midday.
Air temperature	**Highest** from around **12pm till 4pm**, then slowly decreases by 6pm. It finally cools down by night.

[43] Lew Harriman, "Moisture Investigations Using Thermal Cameras," *Journal of National Institute of Building Sciences* (February 2014): 12-14

[44] Elisabetta Rosina and Jonathan Spodek, "Using Infrared Thermography to Detect Moisture in Historic Masonry: A Case Study in Indiana," *APT Bulletin: The Journal of Preservation Technology* 34, no. 1 (2003): 11-16, https://www.jstor.org/stable/1504847

Wall temperature and shade	The east facing west wall receives sun during the morning hours and is covered in shade from the afternoon. The south facing north wall receives sun during the afternoon hours and is covered in shade in morning hours. Therefore, west wall has high temperature just before noon and north wall has high temperature in the afternoon hours.
Solar radiation	As the walls are vertical, the faces of the walls get more radiation when the sun is not directly above (around midday).

Based on the past climate data and preliminary survey, the optimum conditions and timings were finalized to perform a trial passive IRT survey for all the three selected wall areas. (Table 6.2). These optimum timings were selected with the expectation that good thermal images would result, avoiding the issues such as the wall and tree shadows present within the Campo Santo complex.

Table 6.2: Optimum timings for each wall sections to take thermal images

Wall section	**Optimum time for taking thermal images**
North (interior) wall	During afternoon around 2pm-3pm
West (interior) wall towards north end	Late morning hours around 10am-11am
West (interior) wall towards south end	Late morning hours around 10am-11am

6.5 Procedure and instruction for site testing

This research required a site visit to Tumacácori Campo Santo, AZ to take the thermal images and other indirect moisture measurements of the Campo Santo walls. Due to the COVID-19 pandemic and University restrictions, our personal site visit was cancelled, instead the equipment was shipped to the Tumacácori National Park and the site work was performed by Alex Lim (Tumacácori Architectural Conservator) and his co-worker, Garrett Altfilhsch (Figure 6.8).

Figure 6.8: Site testing performed by Garrett, photo by Alex Lim, NPS

Various procedure and instruction manuals were prepared to explain the entire site work, equipment settings and information that was needed to be recorded. Different sets of procedure/ instruction manuals were prepared for all the primary equipment (FLIR E60 thermal camera, Protimeter MMS2 moisture meter and Fieldscout TDR 150 soil moisture meter). For better resolution multiple thermal images of each wall area were taken with an overlap. The entire set of thermal images are stitched together at the end to show the complete wall section thermal readings. Each of the twenty ft wall area was divided into a 2 x 2 ft grid (with the base of the wall at ground level being the reference point). At the points of intersection, the moisture and temperature measurements were recorded using the Protimeter MMS2 pinless moisture meter (Figure 6.9). For the soil in front of each twenty ft wall area, a 2 ft x 3-inch grid was followed, where the vertical lines of the soil (2 ft distance lines) follow the wall grid lines (2 ft distance lines). The base of the wall is the reference point for the soil grid as well. The TDR 150 8-inch probe was completely inserted in to the soil at these points of intersection, and the moisture and temperature readings of the soil were recorded. The NPS had restrictions on inserting a probe into the burial ground soil, so limited readings were taken with the soil probes.

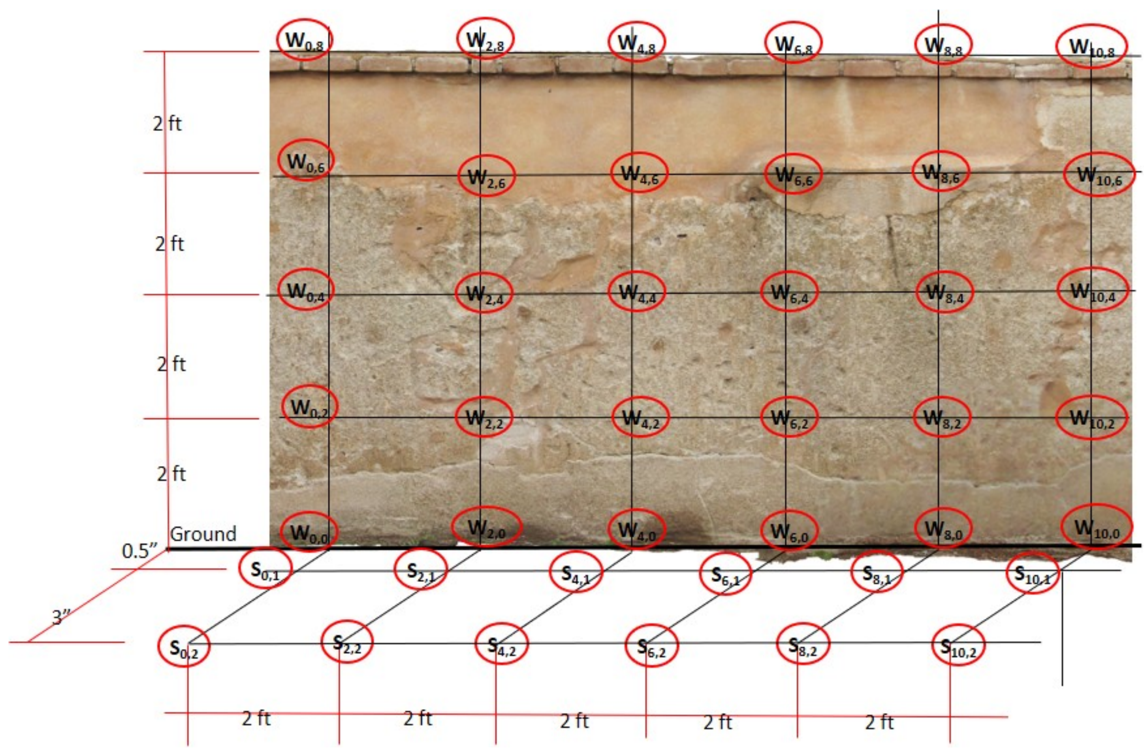

Figure 6.9: A sample half section of the south facing north wall section with wall and soil grid lines

For recording the on-site data, six different sets of data recording sheets for the three wall sections of Campo Santo (two for each section) were prepared to note down all the moisture and temperature readings taken with the indirect moisture meters (See Appendix E, Procedure manuals and data recording sheets).

Chapter 7: Site readings and analysis

7.1 Thermal images, moisture and surface temperature readings

The IRT images, moisture readings and surface temperature readings of the three wall sections were collected on three different days (23rd, 24th and 25th March 2021). The moisture and surface temperature readings taken from different points on the wall surface, using the Protimeter MMS2 were plotted as contour plots using Origin software.[45] The procedure to plot the readings was referred from the OriginLab Graphing tutorial.[46] Thus, two additional data sources and contour plots were generated and used to interpret the IRT images. These plots were used to understand the moisture and surface temperature distribution over the wall area. Every time approximately 44 thermal images were taken for each wall area which had more than 25% overlap between each successive image. These multiple thermal images were merged together to produce the thermal image of an entire wall section.

The thermal image, moisture and surface temperature contour plots were studied together to understand the relationship between moisture and surface temperature of the wall section. On the whole nine sets of data were produced. Where each data set consists of a thermal image, wall moisture contour plot and surface temperature contour plot of each wall sections taken at the same time. Therefore, for three days and three different wall sections - nine different data sets were generated for analysis (see Appendix F). Out of the nine data sets, two of them are shown below, identifying the major factors effecting the temperature gradient of the thermal images (Figures 7.1 and 7.2).

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[45] OriginLab, *OriginPro Graphing & Analysis,* V. Origin 2021, OriginLab. PC. 2021, www.originlab.com
[46] *Graphing: Origin: Contour Plots and Color Mapping Part 1 - Create Contour Plot from a Matrix*, OriginLab Corp. (Youtube, October 29, 2009), 2:26 min., https://www.youtube.com/watch?v=kSpGweGoXXw. No additional settings were used.

Data set 1: South-facing north wall section on 23rd March 2021 (see Appendix F, Figure F.1).

Data set 2: East-facing west wall section towards the north end on 23rd March (see Appendix F, Figure F.2).

Data set 3: East-facing west wall section towards the south end on 23rd March 2021 (see Appendix F, Figure F.3).

Data set 4: South-facing north wall section on 24th March 2021 (see Appendix F, Figure F.4).

Data set 5: East-facing west wall section towards the north end on 24th March 2021 (see Appendix F, Figure F.5).

Data set 6: East-facing west wall section towards the south end on 24th March 2021 (see Appendix F, Figure F.6).

Data set 7: South-facing north wall section on 25th March 2021 (see Appendix F, Figure F.7).

Data set 8: East-facing west wall section towards the north end on 25th March 2021 (see Appendix F, Figure F.8).

Data set 9: East-facing west wall section towards the south end on 25th March 2021 (see Appendix F, Figure F.9).

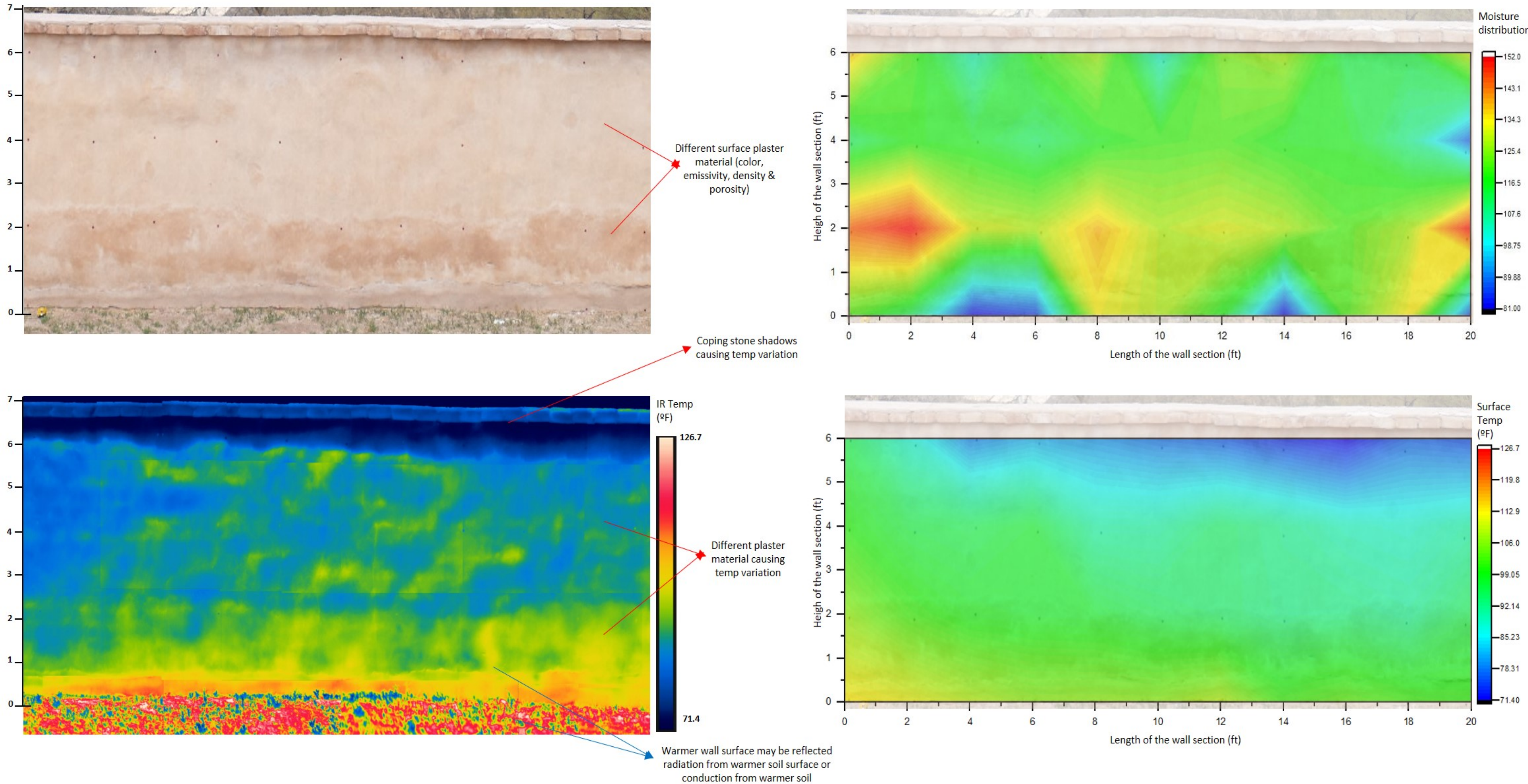

Figure 7.1: (Clockwise starting from top left) Image of east-facing west wall section towards the south end, moisture meter readings contour plot, surface temperature readings contour plot and thermal image. The moisture and surface temperature contour plots (on the right side) have readings up to a height of six feet from ground whereas the left images have the entire wall section.

Conditions: This data set belongs to the east-facing west wall section towards the south end taken on 23rd March 2021 from 10:19am to 11:00am. While taking the readings the air temperature varied from 67.5 ºF to 77.2 ºF, the relative humidity varied from 26.4% to 23.5% and the Dew point varied from 31.5 ºF to 37 ºF. The overall condition was sunny + windy. No soil temperature and moisture data were collected for this case.

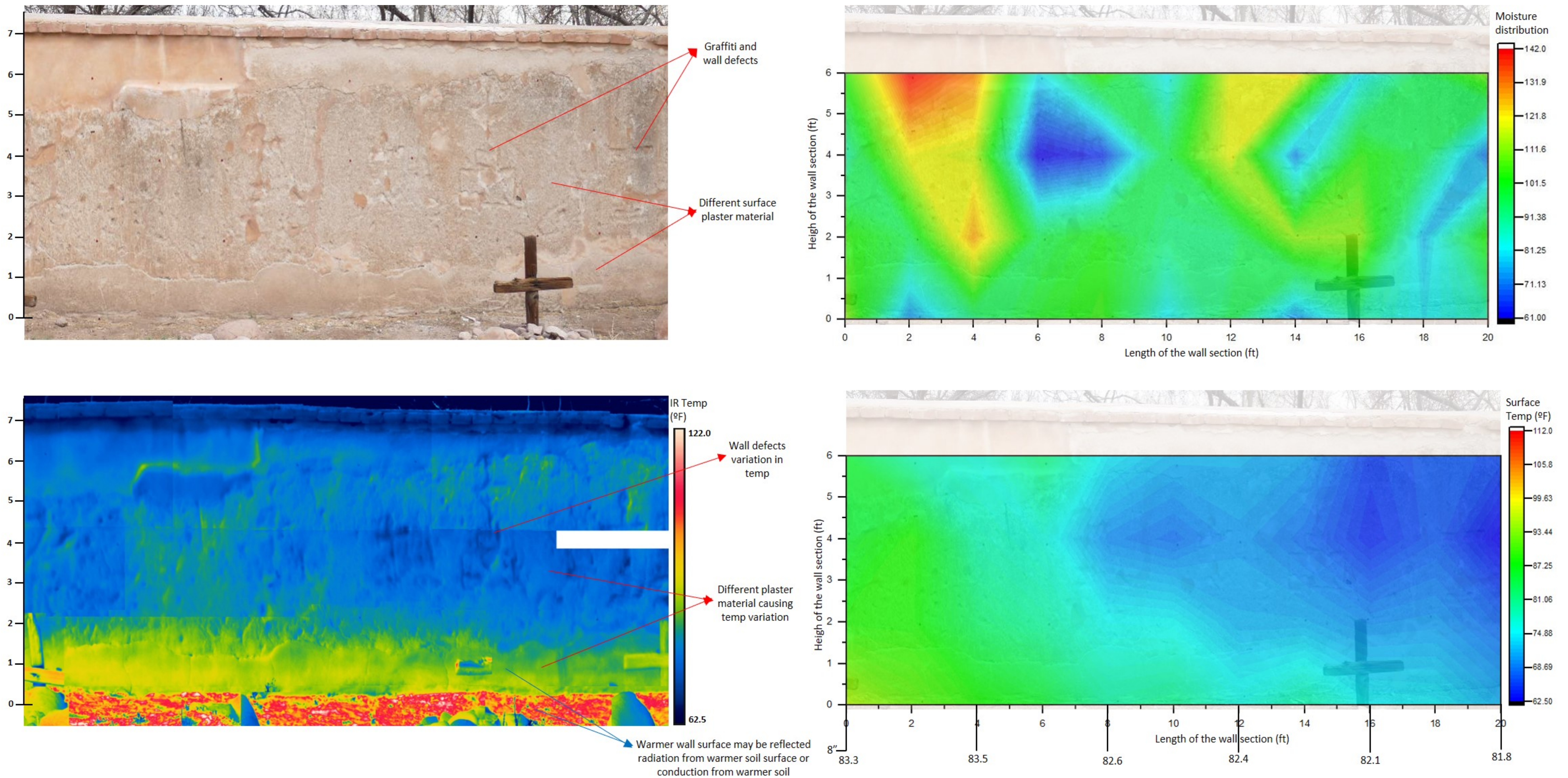

Figure 7.2: (Clockwise starting from top left) Image of south-facing north wall section, moisture meter readings contour plot, surface temperature readings contour plot and thermal image. The moisture and surface temperature contour plots (on the right side) have readings up to a height of six feet from ground whereas the left images have the entire wall section.

Conditions: This data set belongs to the south-facing north wall section taken on 25th March 2021 from 1:35pm to 2:30pm. While taking the readings the air temperature varied from 70.1 ºF to 76.3 ºF, the relative humidity varied from 24.3% to 22.2% and the Dew point varied from 32.7 ºF to 36.3 ºF. There was overcast + windy the entire time. The surface temperature plot also shows the soil temperature (at a depth of 8 inch) in front of the wall, which is lower or similar temperature as the base of the wall. At a depth of 8” the moisture of soil increased as we go away from the wall i.e., the soil moisture value at distance of 3” from the wall is higher than at 0.5” from the wall.

7.2 Analysis of the thermal images, moisture, and surface temperature plots

Our assumption was if the moisture moves from the ground into the walls through capillary action, it will result in a temperature gradient varying from the bottom towards the top of the wall section. Where the bottom of the wall would be at a lower temperature than the upper part of the wall due to evaporative cooling. But we observed a warm band at the bottom of all the IRT images. As the reading were taken in early spring the low air temperature offsets the heating effect of low sun angle. The built-up of heat within the wall was not enough to get evaporative cooling and the lack of warm dry air limited the opportunity for detection of moisture with IRT.

Other factors affecting the IRT images were:

1. ***Difference in surface materials:*** The Campo Santo wall sections do not have uniform lime plaster material throughout the wall area. The history and timeline of the Campo Santo walls indicated that various replastering campaigns were performed throughout the history on the Campo Santo walls. The lower part of the walls consisted of different (later) lime plaster than the rest of the wall section which has the original lime plaster. These different lime plaster surfaces differed in their material properties such as – density and color, which would affect the emissivity of the wall surface. The presence of different emissivity's within the same wall section affected the thermal image readings. Therefore, resulting in different temperature readings for different plaster material, such as the indication of a band of comparatively warm surface temperature at the base of the wall.
2. ***Heat radiation from the soil surface:*** Another reason for the warm band at the base of the wall could be due to the heat emitted from the ground surface. We observed that

the soil temperature, at the depth of 8" around the wall was the same or lower than the base of the wall surface (see TDR soil moisture readings in Appendix F). But the thermal images showed that the surface of the soil had higher temperature due to direct exposure to sunlight. The convective heat emitted at the soil surface, and the radiated heat from the soil surface onto the bottom of the wall might influence the reflected thermal radiation from the plaster at the base of the wall. These factors would result in an elevated IRT reading of surface temperature at the wall base.

All the thermal images, moisture and surface temperature contour plots of all the nine data sets were studied and analyzed to understand the possible correlations and differences. In some of the cases, the surface temperature contour plots showed similar pattern of temperature distribution as that of thermal image taken from IR camera. We were not able to establish a relationship between the moisture and thermal readings for the entire wall sections. Although, it was identified that for some parts of the wall sections, the low temperature readings correlated with high moisture content readings (probably caused by evaporative cooling or the surface material being moist). But this was not applicable for the entire wall section. There were some possible reasons for this inconsistency between moisture and temperature readings. The reasons for variation in thermal images other than moisture are listed below.

- ***Shadows:*** The shadows of the coping bricks at the top of the walls always results in cooler temperature reading below the corner irrespective of the moisture content.
- ***Environmental conditions*** such as a change in cloud cover or wind speed between readings or images

- ***Detachment of plaster or voids at the plaster adobe interface:*** The air layer created between the lime plaster and the adobe due to detachment of plaster can affect the IR reading, due to the additional thermal resistance by the air interface between plaster and adobe. Thus, resulting in change of temperature distribution in the areas with plaster detachment.
- ***Obstructions:*** The wooden crosses placed over the graves/ burials obstruct the direct view of the wall sections when taking a thermal image.
- ***Non-uniform surface material:*** The differences in surface plaster material and properties such as density or color/emissivity can affect the thermal images.
- ***Surface condition***: The surface defects in the plaster, such as cracks or the incised graffiti can affect the thermal readings due to change in thickness of the plaster.
- ***Salts:*** The presence of salts within the wall system might also affect the thermal images due to the release of heat during the crystallization of the salts when the water molecules evaporate from the surface of lime plaster.

Chapter 8: Conclusions and recommendations

8.1 Conclusions

In infrared images are a measurement of thermal energy emitted by, reflected by and transmitted through a structure under specific circumstances can be interpreted to reveal differences in moisture content at or below the surface of the material. For a free-standing exterior adobe wall with lime-plasters, this thesis compared IRT images to surface temperature and moisture readings using capacitance moisture meters in order to differentiate the various factors that might affect accurate interpretation of the IRT image. Contour plots created from the moisture and surface temperature readings proved to be necessary to accurately interpret the IRT images. In addition, measurement of atmospheric conditions and adjacent soil temperature and moisture helped to understand the consequences of emitted and convected heat from the ground and their thermal effects on IRT images of the wall. The contour plots and readings also helped to identify possible discrepancies in the IRT images.

To conclude, the IRT method might not be suitable for non-homogeneous/ non-uniform surface walls of historic structures with defects such as cracks, graffiti, detachment of plaster, bio growth or has different surface plastering material (which differ in color and material properties) for identifying moisture. In case of Campo Santo Tumacácori adobe walls with lime plaster, the IRT alone is not sufficiently accurate to determine the moisture within the plaster finishes or the adobe mass of the walls. The indirect moisture method of capacitance moisture meters is more accurate than IRT for measuring moisture content of the plaster but is time consuming. With both IRT and capacitance moisture measurements, it is important to consider soil moisture content and temperature. However, at the Tumacácori Campo Santo, a burial ground, the use of soil moisture probes was limited by the National Park Services. However, even with constraints on probe depth, soil temperature and moisture measurements were informative. For the in-situ passive IRT images were affected by uncontrollable external factors such as cloud cover, and radiation from surrounding surfaces. Especially for the Tumacácori Campo Santo walls, the variety of the surface materials and their properties such as the color, density, porosity and emissivity, presence of surface defects (graffiti), heat transfer and radiation from the ground surface and salts from the soil moisture largely affected the IRT images.

With either IRT imaging or indirect surface moisture readings, it is important to recognize that surface images/ readings of the plaster material result from hygrothermal transport between the interior adobe bricks to the lime plaster and from the lime plaster to the exterior environment. Without access to the adobe for moisture content and temperature measurements, the interpretation of images and/or data as to the dynamic bidirectional exchange of thermal energy and moisture is limited.

8.2 Recommendations for future use of IRT

In order to confirm the accuracy of the IRT method to identify moisture in Tumacácori's Campo Santo walls, additional testing and readings should be collected under varied conditions and different times of the year. The use of additional indirect moisture monitoring methods such as the capacitance moisture meters, and soil moisture meters proved to be necessary to accurately interpret the IRT images. A similar standard should be followed for future trials, where a comparative study should be done with the moisture and surface temperature plots created from the readings of other indirect moisture monitoring methods along with the thermal images.

While taking IRT images, if the area of the image or the area of the study is too large or larger than the camera view, the thermal images can be taken in parts with an overlap of at least 25% from its successive images. This method would be helpful for merging the images later in post processing phase of the thermal images. For future testing, the process of taking multiple thermal images for large study areas needs to be as fast as possible so that the change in environmental conditions such as cloud cover and shadows have minimum effect on the thermal images. But one should avoid taking large number of thermal images as it might be time consuming during the site testing as well as in merging them together later. It is recommended to take the moisture readings from both sides of the walls to get a better understanding of the thermal images and their relationship with moisture within the wall assembly.

Due to time constraints, the images and readings for this thesis were taken during the late winter season which was not an optimal condition to take the IR images. So, for the future trials, optimum conditions to take the thermal images has to be pre-determined with the help of previous weather data and preliminary site testing before taking the actual images. The recommended optimum conditions for taking thermal images during the day are - high temperature of wall, dry air temperature, low relative humidity around the wall and minimum influence of the sunlight on the wall (no direct sunlight falling on the wall). This might help to get more accurate information on the moisture issues.

Apart from using moisture meters, sounding tests with a rubber or rawhide mallet or electrical hammer is recommend which helps to identify the detached plaster surface and do a better analysis of thermal images of the lime plaster. To check the presence of any metallic materials (like a metal lath used in previous replastering campaigns) within the wall assembly a simple magnetometer is recommended. Prior to taking IRT images, it is suggested to identify the emissivity of the different plaster material found on the surface of the Campo Santo wall sections, which should be accounted while analyzing the thermal images.

Finally, it is important to understand that IRT is only a measure of surface temperature. It is also important to identify all the external factors like atmospheric conditions and site context, and internal factors such as surface anomalies (different plaster materials and properties, defects) that might affect the thermal images. Then it would be easy to accommodate and differentiate all the hygrothermal phenomenon from IRT images and identify the moisture patterns in lime plaster finishes of historic adobe walls.

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Appendices

Appendix A: Tumacácori Campo Santo site photographs

Appendix B: Tumacácori Campo Santo timeline

Appendix C: Soil, topography and climate data

Appendix D: 1979 sieve analysis report and current laboratory testing images

Appendix E: FLIR E60, Protimeter MMS2 and Fieldscout TDR 150 specifications, procedure manuals and data collection sheets

Appendix F: Moisture and surface temperature readings and image datasets from Protimeter and TDR 150

Appendix A: Tumacácori Campo Santo site photographs

Figure A.1: Looking towards the west wall and entrance door of the Campo Santo.

Figure A.2: Looking towards the north east of the Campo Santo with Mortuary Chapel

Figure A.3: Looking towards north west of Campo Santo

Figure A.4: Looking towards north wall of Campo Santo

Appendix B: Tumacácori Campo Santo timeline

Table B.1: Timeline History of Campo Santo, Tumacácori

Start date	End date	Description
1822		Walled cemetery completed to the north of the Franciscan church *(2012 report)* [47]
1864		Cemetery was described as being the same as the corral, perhaps indicating lack of burial mounds at this time. *(2012 report)*
1884		Joe E. Wise of Nogales, AZ and J.M. Jolt used the mission cemetery as a holding pen/ roundup corral for approx. 1,000 cattle, at which time no mission Indian grave mounds were evident. *(2012 report)*
1884		Built double gate with high walls made of wood in the southeast wall of the corner of the cemetery *(2012 report)*
1884		Planted small mesquites established in the cemetery from cattle dung
1900	1908	Cemetery was used by " all of the familied in the area " until 1908 when the mission became a National Monument *(2012 report)*
1908		The site was declared Tumacácori National Monument by President Theodore Roosevelt. A woven wire fence was erected around all the church grounds.
1900	1916	Many graves were dug within north and south portions of the historic cemetery for members of Hispanic families from the town

[47] National Park Service Cultural Landscapes Inventory (2012), Mission San Jose de Tumacácori, Tumacácori National Historical Park

		of Tumacácori. These burials likely disturbed the previous graves of mission Indians and contained above-ground memorial structures. *(2012 report)*
1917	1918	An unconfirmed report by U.S. border guard Corporal Harold Kregar described bodies in the church and against the cemetery wall, possibly accounting for the bullet holes found in the cemetery wall. Other stories state the bullet holes came from the 1940s when area residents used the wall for target practice. *(2012 report)*
Feb 1919		A.S. Noon underpinned 30 to 40 feet of the west cemetery wall and the whole east side of the church "where the adobe wall had badly ground-shaped." *(1977 report)* [48]
May 1919		A.S. Noon reconstructed 80 to 90 feet of the cemetery wall on both the east and west sides and the cemetery gate except for the decorative brick frame. *(1977 report)*
Dec 1923		Pinkley supervised two gangs of adobe brick layers who worked to restore 600 to 700 feet of the cemetery wall to its original height. He found several weaker areas in the wall foundation which the workforce underpinned. In addition, they began to place a concrete cap on the wall and completed the decorative brick frame over the cemetery gate. However, they did not finish the wall cap. *(1977 report)*

[48] Berle Clemensen, "Historic Structure Report: A History of Anglo Period," *Tumacacori National Monument* (1977), NPS, U.S. Department of the Interior, Denver, Colorado.

Feb 1928		Earl Jackson cleaned the cemetery and provided for better drainage of that enclosure as well as making many minor repairs. *(1977 report)*
Jan 1934		The Civil Works Administration began an extensive project at Tumacácori. Workman excavated 400 linear feet of the mission and cemetery foundations to permit repairs. *(1977 report)*
April 1938	Jan 1939	Caywood cleaned the top of the cemetery wall in preparation for capping. Almost 1000 adobe brick were made at the mission for use in bringing the wall to its original height. By June, this task had been completed, but the wall did not receive a cap until January 1939. Only a short selection of the north wall containing the original cap was left untouched. Niches in the cemetery wall, where the stations of the cross had been, were also repaired and readied for plaster. *(1977 report)*
May 1947		Earl Jackson used cement stabilized soil to seal broken areas of original plaster, particularly north end of the mission including the cemetery wall. *(1977 report)*
End of 1950		Earl Jackson directed extensive patchwork on the two-story wall sections which formed part of the east cemetery wall *(1977 report)*
1954		The inside cemetery wall was stabilized with plaster *(2012 report)*
May 1954		Two-year cemetery wall stabilization - work started with the interior wall where metal lath was applied to the adobe at the base

		and cap. It was then plastered using Earl Jackson's formula. *(1977 report)*
June 1954		In June 1954, the interior wall of the cemetery was completed. Stabilization of the exterior wall continued through June 1956. The same process used on the inside of the wall was applied to the outside. The program included strengthening both the interior and exterior original plaster. *(1977 report)*
1970		Areas within the granary and cemetery were excavated preceding stabilization work and the erecting of a shelter that once stood over the granary. Minor test excavations were undertaken in the cemetery *(2012 report)*
1970		West wall cemetery gate doors were replaced *(2012 report)*
1970		A wash of tinted Daraweld bond cement was applied to the exposed cement and earlier stabilization patches *(1972 Henderson report)* [49]
May 1972		Sam Henderson – directed another extensive interior and exterior stabilization program. The only stabilization work performed upon this structure was an application of tinted wash to old patchwork to interior west wall of the cemetery *(1972 Henderson report)*
1979	1980	Minor test excavations were conducted in the cemetery. A trench dug by C. Michael Barton in the Campo Santo revealed a series of

[49] Sam R. Henderson, "Stabilization Report: Tumacácori National Monument," *Ruins Stabilization Unit* (1972), Arizona Archeological Center, Tucson, Arizona.

		well-defined occupation levels from the early mission period. This area was found to be associated with secular functions and domestic activities, indicating that the Campo Santo originally may have been part of the Indian village rather than the mission complex. *(1979/1980 excavation report)* [50]
Aug 1990		The site established as Tumacácori National Historical Park

[50] C. Michael Barton, Kay Simpson and Lee Fratt, "Tumacácori Excavations," *Historic Archaeology at Tumacácori National Monument* (1979 - 1980), Arizona, NPS, U.S. Department of the Interior

Appendix C: Soil, topography and climate data

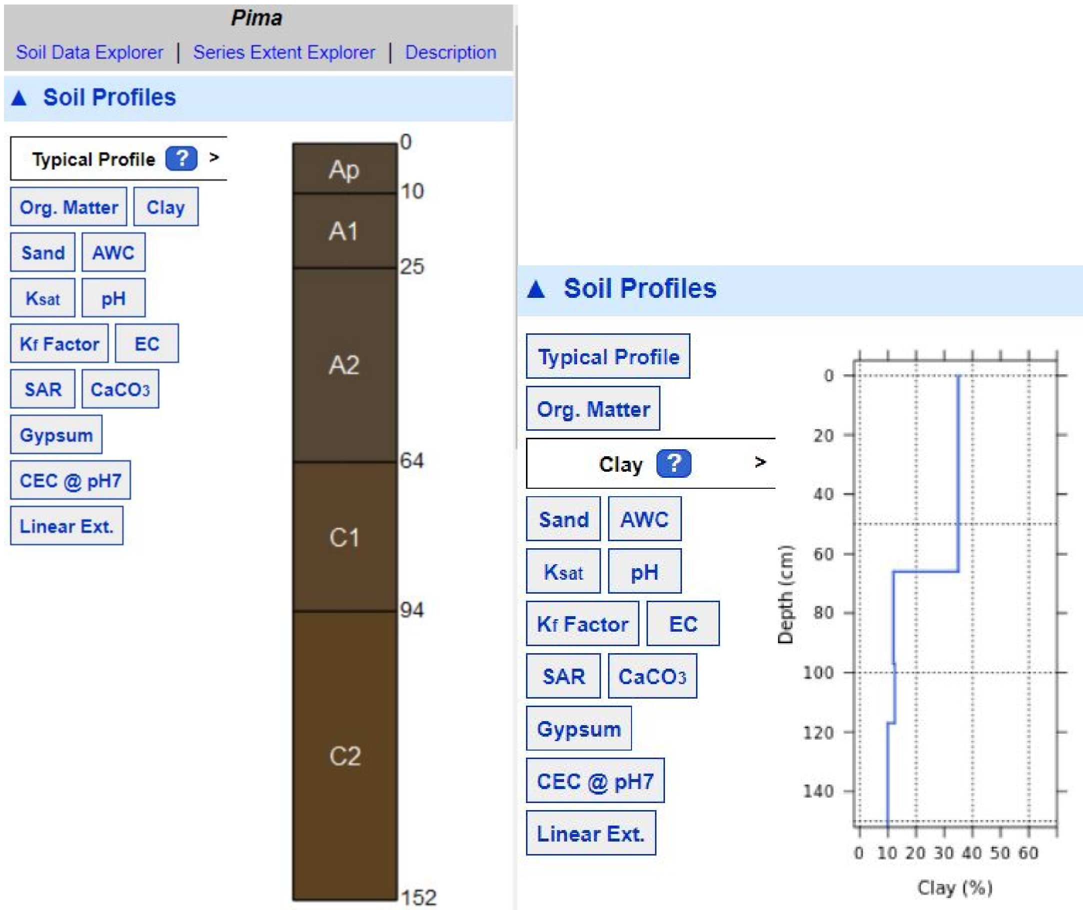


Figure C.1.: The Pima soil profile, Source: https://casoilresource.lawr.ucdavis.edu/gmap/

Soil taxonomy:

Order: Entisols

Suborder: Fluvents Map of Suborders

Greatgroup: Torrifluvents

Subgroup: Anthropic Torrifluvents

Family: Fine-silty, mixed, thermic Anthropic Torrifluvents

Soil Series: Pima

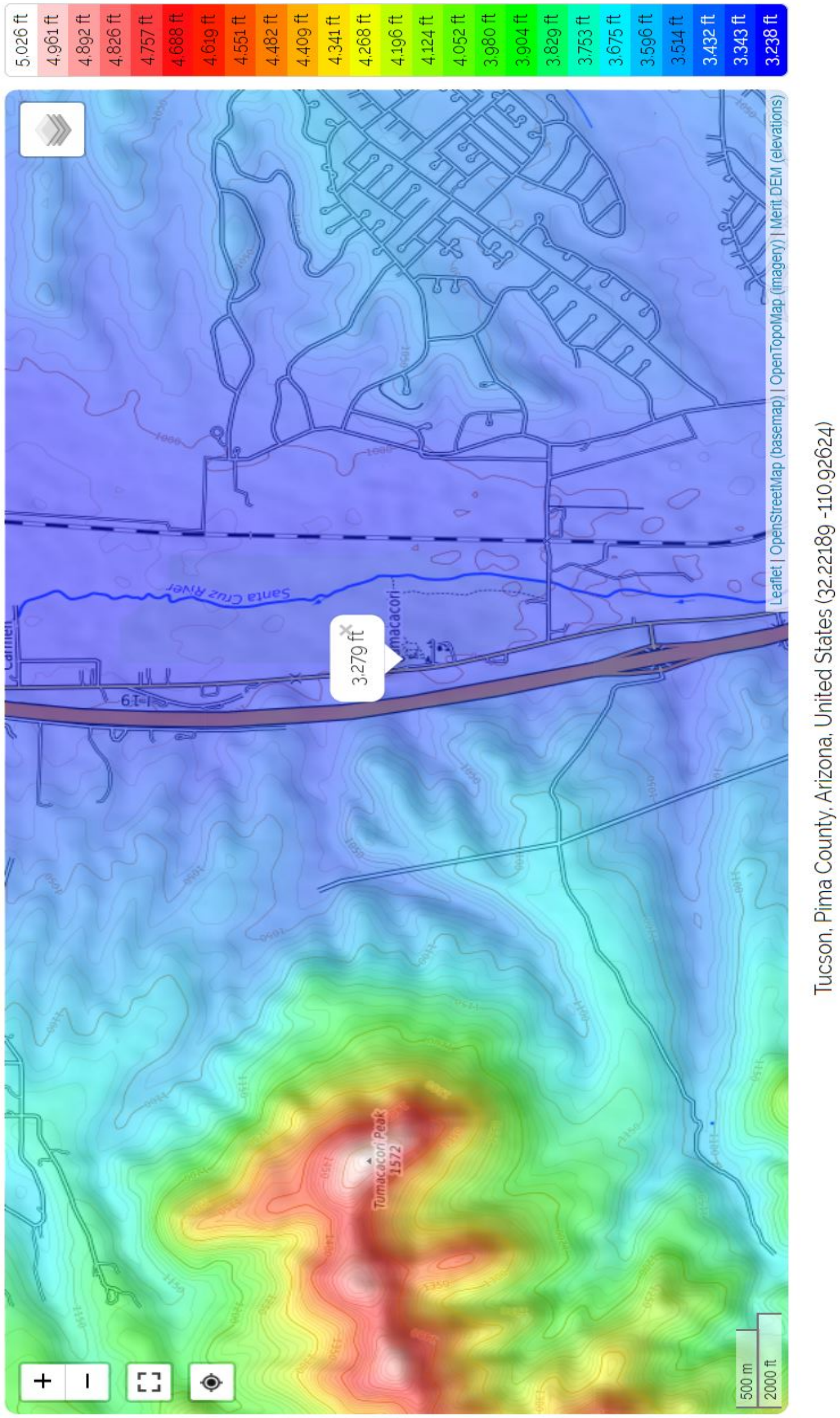


Figure C.2: The topography and elevation of Campo Santo Tumacácori, Source: https://en-us.topographic-map.com/maps/zbv/Tucson/

ASHRAE Climate data of Luke AFB/ Phoenix AZ station, WMO No: 722785 is used to understand the annual solar radiation and wind summary for our Tumacácori site. (Information Credits Michael C. Henry)

Table C.1: The Design Criteria data table for places around the Luke AFB/ Phoenix AZ station

LUKE AFB/PHOENIX AZ	
Latitude = 33.53 N	WMO No. 722785
Longitude =112.30 W	Elevation = 1089 feet
Period of Record = 1967 to 1996	Average Pressure = 28.74 inches Hg

Design Criteria Data

		Mean Coincident (Average) Values			
Dry Bulb Temperature (T)	**Design Value (°F)**	Wet Bulb Temperature (°F)	Humidity Ratio (gr/lb)	Wind Speed (mph)	Prevailing Direction (NSEW)
Median of Extreme Highs	114	72	57	10.6	SW
0.4% Occurrence	110	71	58	9.3	SW
1.0% Occurrence	108	71	60	9.2	SW
2.0% Occurrence	106	71	61	8.6	SW
Mean Daily Range	26	-	-	-	-
97.5% Occurrence	41	36	23	4.4	N
99.0% Occurrence	38	33	21	4.5	N
99.6% Occurrence	35	31	19	4.2	N
Median of Extreme Lows	30	26	13	4.8	N
		Mean Coincident (Average) Values			
Wet Bulb Temperature (T_{wb})	**Design Value (°F)**	Dry Bulb Temperature (°F)	Humidity Ratio (gr/lb)	Wind Speed (mph)	Prevailing Direction (NSEW)
Median of Extreme Highs	79	97	125	7.2	S
0.4% Occurrence	77	98	111	7.0	SSW
1.0% Occurrence	76	97	105	6.9	SSW
2.0% Occurrence	75	96	101	6.5	SSW
		Mean Coincident (Average) Values			
Humidity Ratio (HR)	**Design Value (gr/lb)**	Dry Bulb Temperature (°F)	Vapor Pressure (in. Hg)	Wind Speed (mph)	Prevailing Direction (NSEW)
Median of Extreme Highs	133	85	0.85	4.6	SSW
0.4% Occurrence	123	83	0.79	4.6	N
1.0% Occurrence	116	86	0.74	5.0	SSW
2.0% Occurrence	108	89	0.69	6.2	SSW
Air Conditioning/		$T \geq 93°F$	$T \geq 80°F$	$T_{wb} \geq 73°F$	$T_{wb} \geq 67°F$
Humid Area Criteria	# of Hours	1352	3206	512	1676

Other Site Data

Weather Region	Rain Rate 100 Year Recurrence (in./hr)	Basic Wind Speed 3 sec gust @ 33 ft 50 Year Recurrence (mph)	Ventilation Cooling Load Index (Ton-hr/cfm/yr) Base 75°F-RH 60% Latent + Sensible
10	2.0	90	0.7 + 4.9
Ground Water Temperature (°F) 50 Foot Depth *	Frost Depth 50 Year Recurrence (in.)	Ground Snow Load 50 Year Recurrence (lb/ft²)	Average Annual Freeze-Thaw Cycles (#)
74.4	5	0	2

*Note: Temperatures at greater depths can be estimated by adding 1.5°F per 100 feet additional depth.

Table C.2: The average annual solar radiation table for the sites around Luke AFB/ Phoenix AZ station

Average Annual Solar Radiation – Nearest Available Site

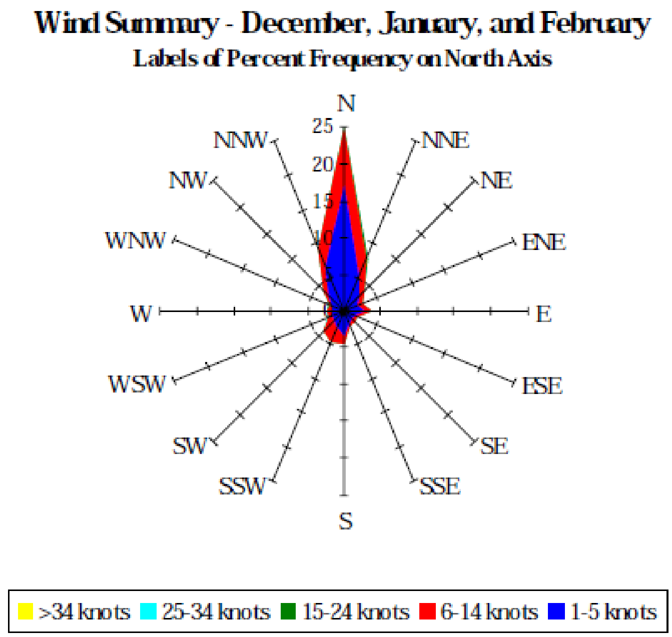
(Source: National Renewable Energy Laboratory, Golden CO, 1995)

City:	PHOENIX
State:	AZ
WBAN No:	23183
Lat(N):	33.43
Long(W):	112.02
Elev(ft):	1112

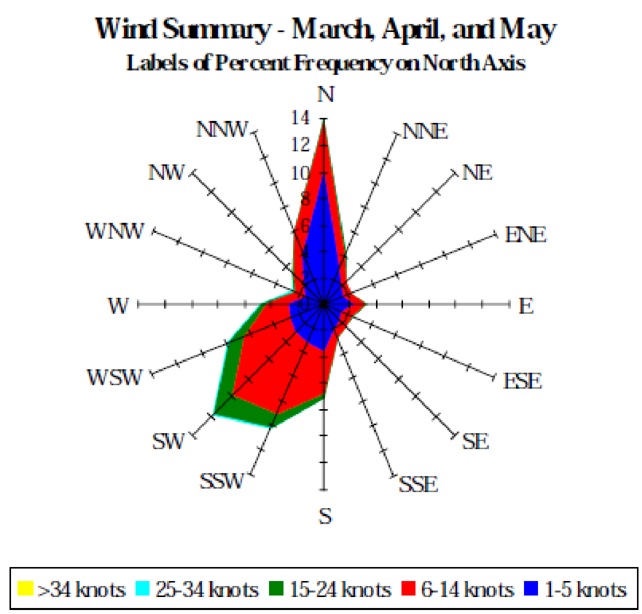
Stn Type:	Primary
SHADING GEOMETRY IN DIMENSIONLESS UNITS	
Window:	1
Overhang:	1.015
Vert Gap:	0.661

AVERAGE INCIDENT SOLAR RADIATION (Btu/sq.ft./day), Percentage Uncertainty = 9

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
HORIZ	Global	1020	1350	1750	2240	2540	2650	2410	2240	1930	1550	1140	930	1810
	Std Dev	76	98	128	90	61	64	89	98	105	83	73	77	47
	Minimum	870	1110	1490	2040	2360	2470	2190	1990	1730	1320	960	680	1670
	Maximum	1150	1510	2010	2440	2620	2760	2580	2390	2130	1680	1250	1080	1860
	Diffuse	330	410	520	560	600	590	710	630	500	410	330	300	490
Clear Day	Global	1190	1530	1990	2420	2680	2760	2660	2440	2090	1640	1250	1080	1980
NORTH	Global	250	310	390	470	620	720	640	510	400	330	260	230	430
	Diffuse	250	310	390	450	500	520	520	470	400	330	260	230	390
Clear Day	Global	230	280	350	440	610	730	660	490	370	300	240	210	410
EAST	Global	670	870	1070	1310	1410	1420	1250	1220	1140	970	750	620	1060
	Diffuse	300	390	480	560	600	610	630	590	510	420	330	280	480
Clear Day	Global	820	1010	1230	1410	1480	1490	1450	1390	1260	1060	850	760	1180
SOUTH	Global	1550	1590	1420	1160	860	720	760	990	1320	1610	1620	1540	1260
	Diffuse	420	490	530	540	530	520	540	540	520	500	440	400	500
Clear Day	Global	2020	1980	1710	1230	870	720	770	1050	1490	1860	1990	1990	1470
WEST	Global	660	840	1040	1260	1370	1420	1280	1230	1120	960	730	610	1040
	Diffuse	310	390	490	560	610	620	630	590	500	430	330	280	480
Clear Day	Global	820	1010	1230	1410	1480	1490	1450	1390	1260	1060	850	760	1180



Percent Calm = 18.78



Percent Calm = 13.43

Figure C.3: (top) Shows the wind direction from December to February and (bottom) shows the wind direction from March to May for places around the Luke AFB/ Phoenix AZ station

Appendix D: 1979 sieve analysis report, current laboratory testing data and images

Paul Wencil Brown, Carl R. Robbins and James R. Clifton. “Adobe II: Factors affecting the durability of adobe structures.” *Studies in Conservation* 24, no. 1 (February 1979): 23-39. https://www.jstor.org/stable/1505920

Table D.1: Shows the sieve analysis of adobe sample taken from the church

TUMACACORI (To_{11}) SIZE FRACTION ANALYSIS

Size fraction mesh per inch (US standard)	*Percent of sample weight*	*X-ray analysis*	*Remarks*
Gravel:			
> 4 mesh	1·39		
< 4 > 8 mesh	3·79		Angular to subrounded grains of quartz and of weathered granites. Occasional rounded quartzite grains
Sand:			
< 8 > 16 mesh	5·99		
< 16 > 30 mesh	8·57	Feldspars, quartz, mica, amphibole	Angular grains of weathered granites, many with biotite, angular to subrounded grains of clear and milky quartz
< 30 > 50 mesh	9·52	,, ,,	Individual grains of feldspars and amphibole also present. Granite fragments decreasing in amounts
< 50 > 100 mesh	8·48	Quartz, feldspars	,, ,,
<100 > 200 mesh	8·26	Quartz, feldspars, mica, amphibole	,, ,,
<200 > 270 mesh	6·79	,, ,,	,, ,,
<270 > 400 mesh	6·45	Quartz, feldspars, mica, amphibole (trace)	Angular quartz is the dominant mineral. Feldspars and mica decreasing
<400 mesh >20 μm	16·67	Quartz, feldspars, mica, illite, amphibole (trace)	,, ,,
Silt:			
(<20 μm > 2 μm)	12·67	Quartz, feldspars, mica and illite	,, ,,
Clay:			
(< 2 μm)	11·24	Quartz, illite, feldspars	
Organic	0·18		Twigs, grass
Soluble salts	1·26		Primarily $CaSO_4 \cdot 2H_2O$ and $CaCl_2$ (chlorides and sulfates of Na, K and Mg likely)

Table D.2: Sieve analysis of the soil sample taken from north east part of the Tumacácori grounds

TUMACACORI SOIL SAMPLE (To_{15}) SIZE FRACTION ANALYSIS

Size fraction mesh per inch (US standard)	*Percent of sample weight*	*X-ray analysis*
Gravel:		
> 4	0·18	
< 4 > 8	0·97	
Sand:		
< 8 > 16	0·85	
< 16 > 30	1·06	Feldspars, quartz, mica
< 30 > 50	1·64	" " "
< 50 > 100	1·58	" " "
< 100 > 200	1·68	Feldspars, quartz, mica, amphibole
< 200 > 270	1·59	" " "
< 270 > 400	1·10	" " "
< 400 > 20 μm	5·89	" " "
Silt:		
(< 20 μm > 2 μm)	37·74	Quartz, feldspars, mica, illite (trace), montmorillonite (trace)
Clay:		
(< 2 μm)	45·54	Quartz, illite, montmorillonite, feldspars, kaolinite, mica
Organic	Nil	
Soluble salts	0·17	

Figure D.1: Indirect porosity measurement of lime plaster experimental samples setup

Table D.3: Porosity and density of lime plaster via Water Absorption method

Porosities of lime plaster samples: Water Absorption method													
	Time (in hrs)	**S1**	**% Water Absorbed**	**S2**	**% Water Absorbed**	**S3**	**% Water Absorbed**	**S4**	**% Water Absorbed**	**S5**	**% Water Absorbed**	**S6**	**% Water Absorbed**
M0 (dry mass)	0	197.27	0	179.06	0	269.77	0	224.21	0	219.13	0	169.83	0
	0.05	226.72	0.15	204.99	0.14	306.62	0.14	254.28	0.13	248.31	0.13	193.93	0.14
	0.25	225.82	0.14	204.8	0.14	306.27	0.14	253.73	0.13	247.98	0.13	193.8	0.14
	0.5	225.81	0.14	204.38	0.14	306.69	0.14	253.71	0.13	248.22	0.13	193.81	0.14
	0.75	225.82	0.14	204.67	0.14	306.7	0.14	253.82	0.13	248.32	0.13	193.85	0.14
	1	225.73	0.14	204.53	0.14	306.67	0.14	253.73	0.13	248.09	0.13	193.83	0.14
	2	225.79	0.14	204.8	0.14	306.8	0.14	253.79	0.13	248.42	0.13	193.71	0.14
	3	225.81	0.14	204.82	0.14	306.81	0.14	253.84	0.13	248.59	0.13	193.62	0.14
	8	226.27	0.15	205.15	0.15	307.45	0.14	254.09	0.13	248.75	0.14	193.85	0.14
	24	227.11	0.15	205.75	0.15	308.32	0.14	254.11	0.13	249.88	0.14	194.65	0.15
	72	230.51	0.17	208.37	0.16	311.88	0.16	257.62	0.15	253.15	0.16	197.64	0.16
	98	230.83	0.17	208.41	0.16	312.37	0.16	257.98	0.15	253.43	0.16	197.99	0.17
	122	230.88	0.17	208.44	0.16	312.12	0.16	257.99	0.15	253.79	0.16	198.11	0.17
	148	231.39	0.17	208.92	0.17	312.67	0.16	258.68	0.15	253.8	0.16	198.26	0.17
	170	231.57	0.17	209.19	0.17	312.87	0.16	258.86	0.15	253.96	0.16	198.35	0.17
	194	231.99	0.18	209.21	0.17	313.15	0.16	259.36	0.16	254.08	0.16	198.71	0.17
	242	232.3	0.18	209.35	0.17	313.26	0.16	259.72	0.16	254.37	0.16	198.97	0.17
	316	232.37	0.18	209.43	0.17	313.26	0.16	259.72	0.16	254.42	0.16	199.03	0.17
M sat (Saturated mass)	**340**	**232.41**	**0.18**	**209.5**	**0.17**	**313.28**	**0.16**	**259.95**	**0.16**	**254.44**	**0.16**	**199.07**	**0.17**
mp (in g)	Mass of water in pores	35.14		30.44		43.51		35.74		35.31		29.24	
Vp (in cm3)	Vol of pores	35.14		30.44		43.51		35.74		35.31		29.24	
Va (in cm3)	Apparent Vol	120		105		160		127		120		100	
% porosity		**29.28**		**28.99**		**27.19**		**28.14**		**29.43**		**29.24**	

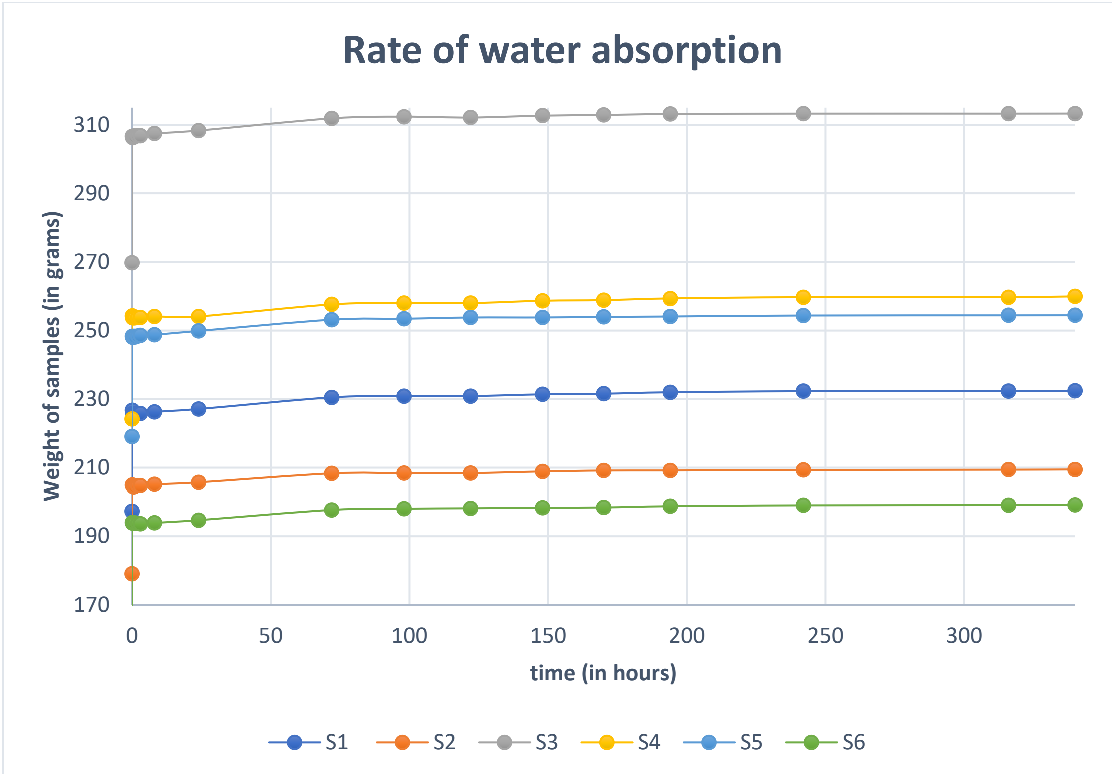


Figure D.2: Graph showing the water absorption rate in lime plaster sample

Figure D.3: Porosity measurement of lime plaster samples by hydrostatic weighing method

Table D.4: Porosity and density of lime plaster via hydrostatic weighing method

Porosities of lime plaster samples: Hydrostatic weighing method							
	Samples	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**
M0	dry wt (g)	197.27	179.06	269.77	224.21	219.13	169.83
M1	Wt in water (g)	114.73	102.53	154.83	130.23	126.73	98.23
M2	Wt in air (g)	233.83	209.75	313.14	262.24	255.39	200.12
Vp (in cm3)	Mp	36.56	30.69	43.37	38.03	36.26	30.29
Va (in cm3)	Apparent Vol	119.1	107.22	158.31	132.01	128.66	101.89
Vr (in cm3)	Real Vol	82.54	76.53	114.94	93.98	92.4	71.6
Pr (in g/cm3)	Real Density	2.39	2.34	2.35	2.39	2.37	2.37
Pa (in g/m3)	Apparent Density	1.66	1.67	1.7	1.7	1.7	1.67
E	**% Porosity**	**30.54**	**28.63**	**27.66**	**28.87**	**28.27**	**29.54**

Figure D.4: Mechanical sieve shaker used in sieve analysis test

Figure D.5: Separated sieve samples of adobe sample 1

Table D.5: Sieve analysis calculations for Adobe sample 1

Sample 1	Total Wt: 400g	Munsell color: 7.5 YR 4/3 brown		
	Sieve no	**Sieve size (µm)**	**Sample retained (g)**	**% mass retained**
Gravel	4	4750	11.53	2.88
Sand	8	2360	15.18	3.8
	16	1180	34.37	8.59
	30	600	53.74	13.44
	50	300	82.99	20.75
	100	150	89.79	22.45
	200	75	51.58	12.9
Silt + Clay	Pan	0	60.39	15.1
	Total sample after sieving		**399.57**	**99.91**

Figure D.6: Separated sieve samples of adobe sample 2

Table D.6: Sieve analysis calculations for Adobe sample 2

Sample 2	Total Wt: 380g	Munsell color: 7.5 YR 4/2 brown		
	Sieve no	**Sieve size (μm)**	**Sample retained (g)**	**% mass retained**
Gravel	4	4750	28.37	7.47
Sand	8	2360	11.08	2.92
	16	1180	33.69	8.87
	30	600	48	12.63
	50	300	66.21	17.42
	100	150	72.67	19.12
	200	75	48.55	12.78
Silt + Clay	Pan	0	71.4	18.79
	Total sample after sieving		**379.97**	**100**

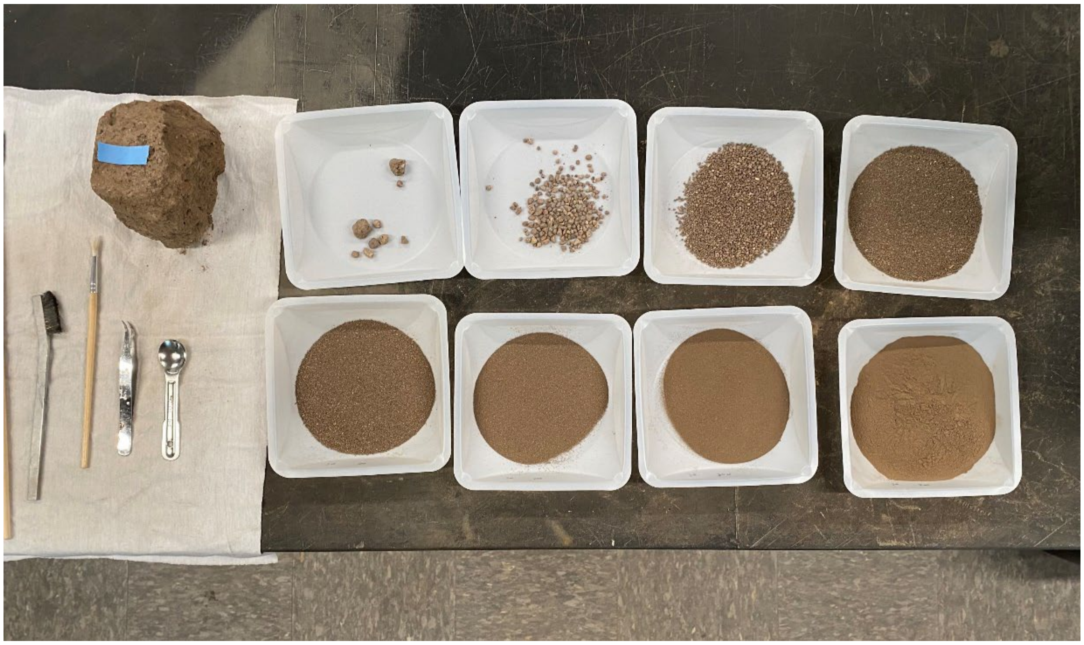


Figure D.7: Separated sieve samples of adobe sample 3

Table D.7: Sieve analysis calculations for Adobe sample 3

Sample 3	Total Wt: 220g	Munsell color: 7.5 YR 4/2 brown		
	Sieve no	**Sieve size (μm)**	**Sample retained (g)**	**% mass retained**
Gravel	4	4750	6.55	2.98
Sand	8	2360	8.72	3.96
	16	1180	22.81	10.37
	30	600	30.05	13.66
	50	300	28.21	12.82
	100	150	31.96	14.53
	200	75	29.68	13.49
Silt + Clay	Pan	0	61.92	28.15
	Total sample after sieving		**219.9**	**99.96**

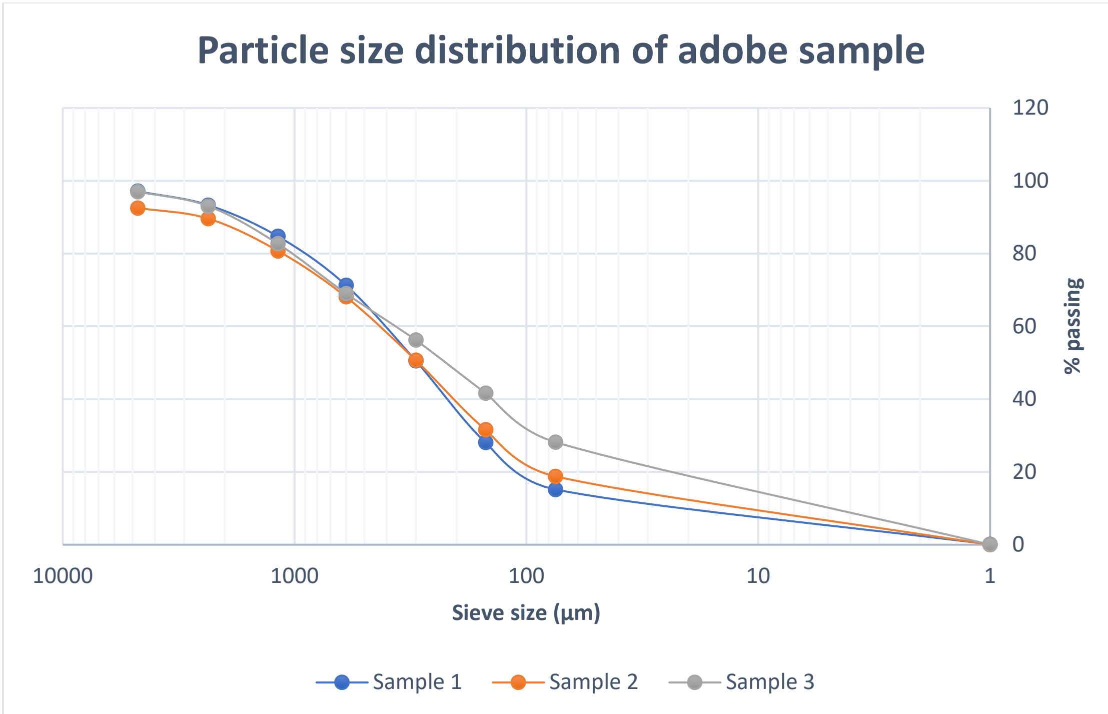


Figure D.8: Particle size distribution graph of Tumacácori Campo Santo adobe samples

Appendix E: FLIR E60, Protimeter MMS2 and Fieldscout TDR 150 specifications, procedure manuals and data collection sheets

Specifications

FLIR E60 Thermal Camera: FLIR Exx series user manual
https://www.flir.com/globalassets/imported-assets/document/flir-exx-series-user-manual.pdf

Specifications	**Ranges**
IR resolution	320 × 240 pixels
Thermal sensitivity/NETD	< 0.05°C @ +30°C (+86°F) / 50 mK
Field of view (FOV)	25° × 19°
Minimum focus distance	0.4 m (1.31 ft.)
Focal length	18 mm (0.7 in.)
Focus	Focus Manual
Spectral range	7.5–13 µm
Image modes	IR image, visual image, MSX, picture in picture, thumbnail gallery
Object temperature range	–20°C to +120°C (–4°F to +248°F) 0°C to +650°C (+32°F to +1202°F)
Accuracy	±2°C (±3.6°F) or ±2% of reading, for ambient temperature 10°C to 35°C (+50°F to 95°F)
Automatic hot/cold detection	Auto hot or cold spot meter markers within area
Emissivity correction	Variable from 0.01 to 1.0 or selected from materials list
Color palettes	Arctic, Gray, Iron, Lava, Rainbow and Rainbow HC
Set-up commands	Local adaptation of units, language, date and time formats
Image storage mode	Simultaneous storage of images in IR, visual and MSX

Built-in digital camera	3.1 Mpixel (2048 × 1536 pixels), and one LED light
Digital camera, focus	Fixed focus
Storage SD Card	One card slot for removable SD memory cards
Battery operating time	Approx. 4 hours at +25°C (+77°F) ambient temperature and typical use
Charging time	Charging time 4 h to 90% capacity, charging status indicated by LED's
Start-up time from sleep mode	Instant on
Operating temperature range	–15°C to +50°C (+5°F to +122°F)
Storage temperature range	–40°C to +70°C (–40°F to +158°F)
Humidity (operating and storage)	IEC 60068-2-30/24 h 95% relative humidity +25°C to +40°C (+77°F to +104°F) / 2 cycles
Camera weight, incl. battery	0.869 kg (1.91 lb.)
Camera size (L × W × H)	246 × 97 × 184 mm (9.7 × 3.8 × 7.2 in.)

TDR 150 Soil Moisture Meter with Case (https://www.specmeters.com/soil-and-water/soil-moisture/fieldscout-tdr-meters/tdr-150-soil-moisture-meter-with-case/)

(Also calculates the soil temperature so no need of separate soil temperature meter)

Specifications	**Ranges**
Measurement Principle	Time - domain measurement methods
Measurement Units	Percent Volumetric Water Content (VWC)
Resolution:	0.1% VWC
Accuracy:	+- 3.0% VWC with Electrical Conductivity (EC) < 2 mS/cm
Range:	0% to saturation (Saturation up to about 50% volumetric water depending on soil type)
Battery/Life:	4 AA lithium batteries; approximately 100,000 readings without backlight
Data Logger:	50,000 measurements
EC	Range: 0 to 5 mS/cm, Resolution: 0.01 mS/cm, Accuracy: +/- 0.1 mS/cm
Temperature	Range: -30°C to 60°C, Resolution: 0.1°, Accuracy: +/- 1°C

Additional equipment necessary for TDR 150:

- TDR rods – two 8 in (20cm) rods (https://www.specmeters.com/tdr-rods/)
- Pilot hole maker for TDR meters (https://www.specmeters.com/pilot-hole-maker/?keyword=Pilot-Hole%20Maker%20For%20TDR%20Meters)

Protimeter MMS2 BLD8800 Moisture meter (https://www.protimeter.com/mms2.html)

(Used Pinless moisture meter for this research)

Specifications	Range
Gross Weight	Meter with battery 6.27oz (178 gms)
Dimensions (L X W X H)	7 in x 2.75 in x 1.9 in (180 mm x 70 mm x 49 mm) 7 1/2 in.x 3 3/4 in max
Maximum needle depth	0.4 in (10 mm)
Display	Color LCD
Batteries (included)	1x9 V
Warranty	24 months on mechanical or manufacturing defects. Does not include wearing part or accessories.
Moisture measurement range	Pin (% WME) 8 to 99, readings over 30% are relative. Non-invasive (RF) up to 3/4 in (19mm) deep 60 to 1000 (relative)
IR Surface Temperature probe range	15°F to 120°F (-10°C to 50°C)
Hygrostick data (Nominal)	30% to 40% RH (±3% RH) at 68°F (20°C) 41% to 98% RH (±2%) at 68°F (20°C) Range 32°F to 122°F (0°C to 50°C) ±0.6°F (±0.3°C)
Quickstick data (Nominal)	0% to 10% RH, ±3% RH at 68°F (20°C) 10 to 90% RH, ±2% RH at 68°F (20°C) Range 32°F to 122°F (0°C to 50°C) ±0.6%°F (±0.3°C) Nominal response 30% to 90% and back to 30% RH in 45 seconds @ 68°F (20°C)
Data Storage	Store up to 1,000 results with date and time stamp from all instrument functions

<u>Procedure Manuals</u>

FLIR E60 Thermal camera: Same settings were used for all the recordings in this thesis

Refer the FLIR E60 series manual for procedure and steps for changing various settings.

https://www.flir.com/globalassets/imported-assets/document/flir-exx-series-user-manual.pdf

Settings	Selection
Units	ºF & feet/inches
Focus	Manual focus - adjust while taking the thermal image
Temperature scale	Auto
Color palette	Rainbow
Emissivity	0.86 for plaster (based on FLIR manual)
Object distance	10 feet
Saving options	Save both the thermal & visual image (default)
Storage options	Camera stores the image file on the memory card

All the other settings remain standard based on the FLIR Exx series manual

After the thermal images are collected and stored in the SD card, they are transferred into the computer for further analysis. The FLIR software Tools is used for post processing of the thermal images.

The temperature range for thermal images of each wall section is standardized by changing the maximum and minimum values. Thus, providing same temperature scale for all the images of the same wall section. The multiple images of each wall section with changed temperature range from auto to standard range (same min and max value for the images) are merged together to produce a thermal image of a complete wall section.

FieldScout TDR 150 Soil Moisture meter Settings and Procedure Manual

Different Settings and Modes:

Settings Menu

On/Off | Back 

Delete | Up 

Menu | Select 

Read | Down 

General Settings Menu:

Press the **MENU** button to enter the Settings menu

Settings	Selection
Rod Length	Select LONG 8” rod length
Soil type	**Standard:** for most mineral soils/ **Hi-Clay: for soils with higher clay content (>27%) / Sand:** for sand-based fields or turf greens
Save to USB	Transfer’s data logs to a USB flash drive if attached
Backlight	Select ON/ OFF/ AUTO based on necessity
GPS	Enabled
Bluetooth	Disabled
Sound	ON/ OFF
Temp Source	Select soil sensor
Temp Units	Select Fahrenheit Scale
Moisture type	VWC %
EC Units	Salinity Index
Current Date	Enter current date
Current Time	Enter current time
Timezone	GMT -7
Daylight savings	ON

Procedure

Note: Check the battery before taking the measurements. Use the pilot hole maker to make the holes in the soil to avoid any damage to the rods.

The measurements are taken at the points of intersection of the grid made on soil (similar to that of grid made on walls) at the base of the selected wall sections.

Step 1: Briefly press the power on button

Step 2: Press **MENU** button to open the Settings Menu

Step 3: Set up the general settings like: Rod length, Soil type, Temperature Source, Temperature Units, Moisture type, EC Units, current date and time

Step 4: Selected the point on the soil where you want to take the measurements

Step 5: Grip the TDR sensor block. Push down on the block, maintaining a steady downward pressure to drive the rods into the soil until the sensor base is in contact with the soil surface. Be sure not to allow back and forth or side to side movement. This can introduce air pockets into the soil medium which will alter the reading.

Note: Exercise care not to damage the rods.

Step 6: Press the **READ** button and observe the change in results on the top display.

Step 7: Record the Soil Temperature **(Soil Temp)** in the center of the readingcreen**,** Volumetric Water content **(VWC)** at the right bottom of the reading screen and the **salinity index** at the left bottom of the reading screen.

Step 8: Repeat the step 4 to 7 for different points on the soil

Protimeter MMS2 Settings and Procedure Manual

Different Settings and Modes:

Turn on by pressing the center button  . To navigate use up  , right  , down  and back button.

In the main menu you can “Select Mode” based on the required measurement.

<u>BASIC SETTINGS</u>

1. Go to Main menu and select “SETTINGS” where a secondary menu opens to set the units, date and time, brightness.
2. In the secondary menu select “UNITS” and in that select “Non-metric” and press enter.

(Navigate to SELECT MODE > SETTINGS > UNITS > Non-metric)

3. Then set the date and time from the settings menu (can also be set with MMS2 software).

(Navigate to SELECT MODE > SETTINGS > DATE AND TIME and press to change the date and time)

4. Choose the minutes you can leave the meter to stay on after pressing the last button from the “AUTO OFF” option in Settings menu.

(Navigate to SELECT MODE > SETTINGS > AUTO OFF and press to configure the Auto off time)

5. Then set the appropriate brightness as per your requirement from the Setting menu

(Navigate to SELECT MODE > SETTINGS > SET BRIGHTNESS and press to set the Brightness level)

6. Buzzer on-off
7. Set logging: Start after/ Log interval/ Stop after/ Job number

<u>TO RECORD RELATIVE HUMIDITY AND TEMPERATURE</u>

1. Go back to main menu and select the “**HYGROMETER MODE**”. There is a humidity sensor at the back of this instrument.

(Navigate to and press to select the SELECT MODE > HYGROMETER for Hygrometer mode)

2. Note the Relative Humidity **(RH)** in % and Temperature **(TEMP)** in ^{o}F.

TO RECORD THE DEW POINT

1. Go back to main menu and select the "**PSYCHROMETRICS MODE**"

(Navigate to SELECT MODE > PSYCHROMETRICS and press to select the Psychrometrics mode)

2. A secondary menu opens from which you can choose the Dew point.

(Navigate to SELECT MODE > PSYCHROMETRICS > DEW POINT and press to get the Dew Point reading)

3. Note the Dew point **(DP)** in °F

TO RECORD THE WALL MOSITURE

1. Go back to the main menu and select the **"PINLESS MOISTURE METER MODE".**

(Navigate to SELECT MODE > PINLESS MOISTURE METER and press to select the Pinless Moisture meter mode)

2. When the Pinless Moisture Meter mode is selected, the device will display the surface moisture in terms of *Wood Moisture Equivalent* count.
3. Place the instrument back on the surface of the wall, make sure the wall surface is flat.
4. Note down the **relative value number (MC)**, **the color indication** (Green **(G)**/ Yellow **(Y)**/ Red **(R)**) and the **reference reading** (Dry / At risk/ Wet)
5. **Note:** If metal is present below the surface, the MMS2 may give a false positive

TO RECORD SURFACE TEMPERATURE

1. Hold the IRT button  to enable the IR Thermometer. Release the button and press it again within 1 second to enable the **LASER** pointer. The **LASER** pointer will indicate the area on the surface where the measurement is being taken.
2. Remove the cap to allow the laser (emitted) to come out.
3. Note down the **IR Temperature (Sur Temp**) in °F and **the differential temperature to dew point (Surf T. Diff)** in °F. And the **Condensation status** (Condensation/ Risk of condensation/ No Condensation)

<u>Procedure</u>

Note: Check the battery before taking the measurements

Step 1: Note down the date, time and recorder name on the top of the recording sheet

Step 2: After setting up the general settings like: units, date and time, brightness, etc.

Step 3: Record the Relative Humidity, Temperature and Dew point of the place

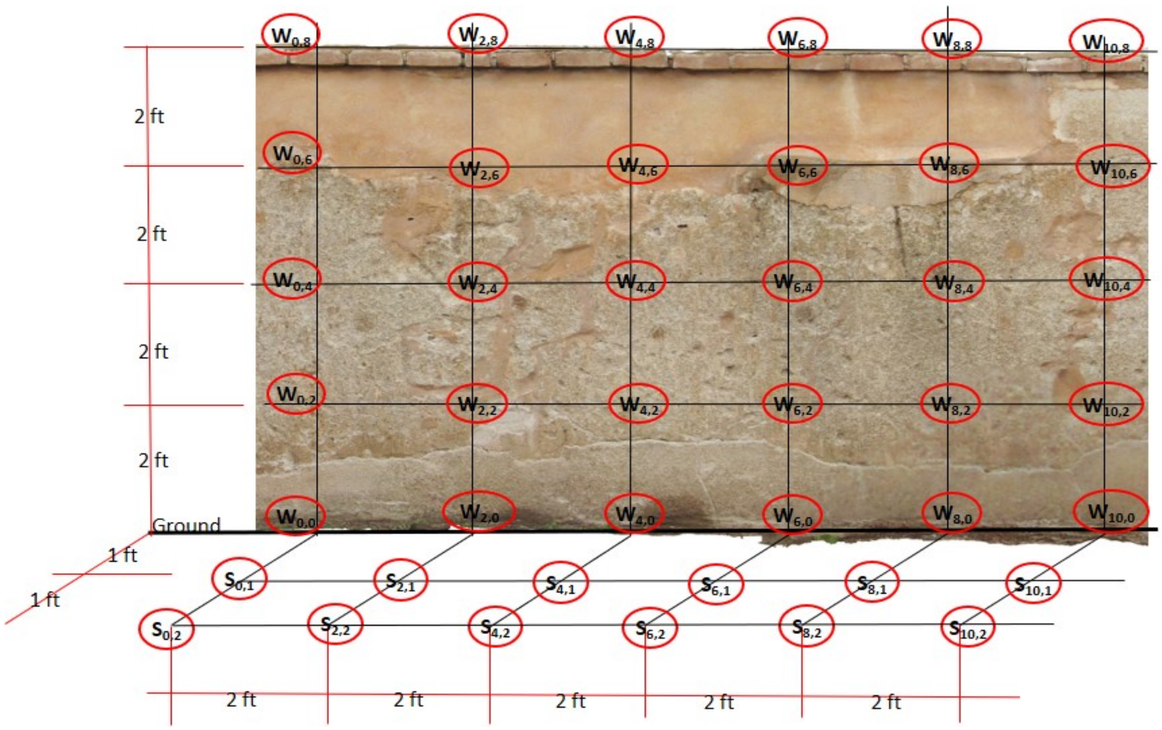
Step 4: Then place the moisture meter on each point of intersection and record the **moisture content number (MC)**, color indicator (**G** for Green, **Y** for Yellow and **R** for Red) or reference reading (Dry / At risk/ Wet).

Step 5: Record the **surface temperature (Sur Temp)** at each point using the IR laser, the differential temperature **(Surf T. Diff)** and **condensation status** (**C** for Condensation / **R** for Risk of Condensation/ **NC** for No Condensation.

Data recording sheets

Sample recording datasheet for south-facing north wall section part 1

General data from Protimeter MMS2:	General setting of TDR 150:	Sheet No: 1 / 6
Air Temp (ºF): RH: Dew point:	Rod length: **(L)** Long (8”) Soil type: Standard/ Hi-Clay/ Sand Moisture type: VWC%	Date: Time: Recorder initials:

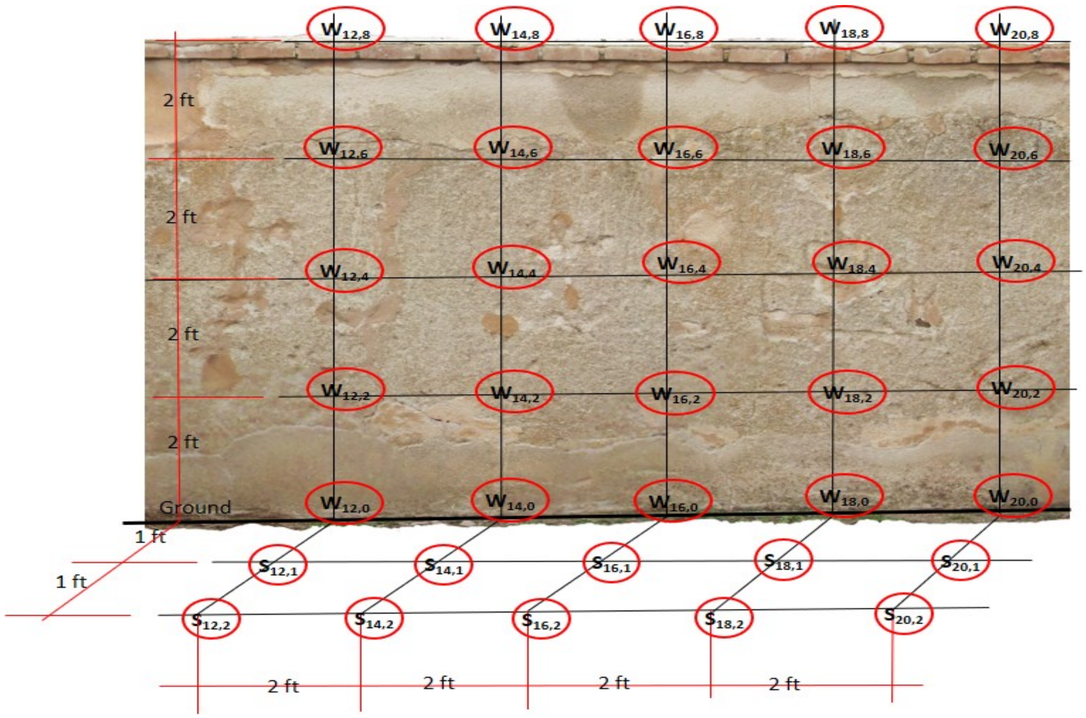


MC Sur Temp (ºF) Surf. T Diff (ºF)	$W_{(0,8)}$	$W_{(2,8)}$	$W_{(4,8)}$	$W_{(6,8)}$	$W_{(8,8)}$	$W_{(10,8)}$
MC Sur Temp (ºF) Surf. T Diff (ºF)	$W_{(0,6)}$	$W_{(2,6)}$	$W_{(4,6)}$	$W_{(6,6)}$	$W_{(8,6)}$	$W_{(10,6)}$
MC Sur Temp (ºF) Surf. T Diff (ºF)	$W_{(0,4)}$	$W_{(2,4)}$	$W_{(4,4)}$	$W_{(6,4)}$	$W_{(8,4)}$	$W_{(10,4)}$

MC Sur Temp (ºF) Surf. T Diff (ºF)	$W_{(0,2)}$	$W_{(2,2)}$	$W_{(4,2)}$	$W_{(6,2)}$	$W_{(8,2)}$	$W_{(10,2)}$
MC Sur Temp (ºF) Surf. T Diff (ºF)	$W_{(0,0)}$	$W_{(2,0)}$	$W_{(4,0)}$	$W_{(6,0)}$	$W_{(8,0)}$	$W_{(10,0)}$
Soil Temp (ºF) VMC (%) Salinity index	$S_{(0,1)}$	$S_{(2,1)}$	$S_{(4,1)}$	$S_{(6,1)}$	$S_{(8,1)}$	$S_{(10,1)}$
Soil Temp (ºF) VMC (%) Salinity index	$S_{(0,2)}$	$S_{(2,2)}$	$S_{(4,2)}$	$S_{(6,2)}$	$S_{(8,2)}$	$S_{(10,2)}$
Additional notes:						

Sample recording datasheet for south-facing north wall section part 2

General data from Protimeter MMS2: Air Temp (ºF): RH: Dew point:	General setting of TDR 150: Rod length: **(L)** Long (8") Soil type: Standard/ Hi-Clay/ Sand Moisture type: VWC%	Sheet No: 2 / 6 Date: Time: Recorder initials:



MC Sur Temp (ºF) Surf. T Diff (ºF)	W(12,8)	W(14,8)	W(16,8)	W(18,8)	W(20,8)
MC Sur Temp (ºF) Surf. T Diff (ºF)	W(12,6)	W(14,6)	W(16,6)	W(18,6)	W(20,6)
MC Sur Temp (ºF) Surf. T Diff (ºF)	W(12,4)	W(14,4)	W(16,4)	W(18,4)	W(20,4)
MC	W(12,2)	W(14,2)	W(16,2)	W(18,2)	W(20,2)

Sur Temp (ºF) Surf. T Diff (ºF)					
MC Sur Temp (ºF) Surf. T Diff (ºF)	$W_{(12,0)}$	$W_{(14,0)}$	$W_{(16,0)}$	$W_{(18,0)}$	$W_{(20,0)}$
Soil Temp (ºF) VMC (%) Salinity index	$S_{(12,1)}$	$S_{(14,1)}$	$S_{(16,1)}$	$S_{(18,1)}$	$S_{(20,1)}$
Soil Temp (ºF) VMC (%) Salinity index	$S_{(12,2)}$	$S_{(14,2)}$	$S_{(16,2)}$	$S_{(18,2)}$	$S_{(20,2)}$
Additional notes:					

<u>Image Abbreviations</u>

$W_{(x,y)}$ / $S_{(x,y)}$ – Point of intersections of the grid

W: Indicates that the point is on wall

S: Indicates that the point is on ground soil

X: Indicates the distance of the point in horizontal direction from the reference point

Y: indicated the distance of the point in vertical direction from the reference point

Reference point is $\mathbf{W_{(0,0)}}$ at the ground

<u>Table Abbreviations</u>

Sur Temp (ºF): Surface temperature of the wall at that point

Sur Temp Diff (ºF): How was is the surface temperature from dew point/ condensation

MC: Moisture content at that point (Note: Record the number as well as the color indication – **R** for Red/ **Y** for Yellow/ **G** for Green)

Soil Temp (ºF): Soil Temperature at that point

VWC (%): Volumetric water content of the soil at that point

Salinity index: Gives the electrical conductivity of the soil

General data Abbreviations

Air temp (ºF): Surrounding Air temperature of the surrounding environment while taking the readings

RH (%): Relative humidity of the surrounding environment while taking the readings

DP : Dew point of the surrounding environment while taking the readings

Appendix F: Moisture and surface temperature readings and image datasets from Protimeter MMS2 and Fieldscout TDR 150

Table F.3: Moisture and surface temperature readings collected on 23rd March 2021

Date: 3/23/2021											
North wall		Air temp: 73.9 ºF			Air temp: 78.2 ºF						
		RH: 22.2%			RH: 20%						
Windy + Sunny		DP: 33 ºF			DP: 35.2 ºF						
		Time: 1:43pm			1:55pm		Recorded by: Alex Lim & Garrett				
	$W_{(0,6)}$	$W_{(2,6)}$	$W_{(4,6)}$	$W_{(6,6)}$	$W_{(8,6)}$	$W_{(10,6)}$	$W_{(12,6)}$	$W_{(14,6)}$	$W_{(16,6)}$	$W_{(18,6)}$	$W_{(20,6)}$
MC	129D	152D	137D	77D	124D	104D	120D	128D	88D	107D	91D
Sur Temp (ºF)	97.1	98.1	94.4	100	95.4	91.1	95	91.7	89.4	91.1	92.2
Surf. T Diff (ºF)	61.8	61.8	59.8	65.9	60.3	56	59.3	36.2	55.3	56.3	55.9
	$W_{(0,4)}$	$W_{(2,4)}$	$W_{(4,4)}$	$W_{(6,4)}$	$W_{(8,4)}$	$W_{(10,4)}$	$W_{(12,4)}$	$W_{(14,4)}$	$W_{(16,4)}$	$W_{(18,4)}$	$W_{(20,4)}$
MC	115D	131D	94D	86D	83D	73D	108D	104D	97D	79D	123D
Sur Temp (ºF)	96.8	103.4	98.7	96.3	92.4	89.9	94.3	93.3	89.5	86.5	91.3
Surf. T Diff (ºF)	62	68.1	64.9	60.9	57.2	55.8	60.9	56.6	54.5	53.3	55
	$W_{(0,2)}$	$W_{(2,2)}$	$W_{(4,2)}$	$W_{(6,2)}$	$W_{(8,2)}$	$W_{(10,2)}$	$W_{(12,2)}$	$W_{(14,2)}$	$W_{(16,2)}$	$W_{(18,2)}$	$W_{(20,2)}$
MC	104D	108D	124D	88D	115D	82D	88D	96D	78D	66D	104D
Sur Temp (ºF)	102.8	103.6	101.4	101.1	97.9	101.1	98.7	101.1	98.1	93.8	94.4
Surf. T Diff (ºF)	65.9	68.5	62.5	65.9	63.9	65.9	61.9	63.1	61.8	60.7	59
	$W_{(0,0)}$	$W_{(2,0)}$	$W_{(4,0)}$	$W_{(6,0)}$	$W_{(8,0)}$	$W_{(10,0)}$	$W_{(12,0)}$	$W_{(14,0)}$	$W_{(16,0)}$	$W_{(18,0)}$	$W_{(20,0)}$
MC	107D	96D	97D	96D	96D	100D	83D	81D	81D	91D	66D
Sur Temp (ºF)	113.6	112.8	112.2	111.7	107	109.7	107.8	113.1	110.2	106	104.1
Surf. T Diff (ºF)	78.3	78.1	76.6	77.7	73.4	74.1	72.9	75.9	75.5	72.3	70
Soil Temp (ºF)	$S_{(0,0.5)}$	$S_{(2,0.5)}$	$S_{(4,0.5)}$	$S_{(6,0.5)}$	$S_{(8,0.5)}$	$S_{(10,1)}$	$S_{(12,0.5)}$	$S_{(14,0.5)}$	$S_{(16,0.5)}$	$S_{(18,0.5)}$	$S_{(20,0.5)}$
Soil Temp (ºF)						NO DATA					
VMC (%)											
Salinity index (mS/cm)											
Soil Temp (ºF)	$S_{(0,3")}$	$S_{(2,3")}$	$S_{(4,3")}$	$S_{(6,3")}$	$S_{(8,3")}$	$S_{(10,3")}$	$S_{(12,3")}$	$S_{(14,3")}$	$S_{(16,3")}$	$S_{(18,3")}$	$S_{(20,3")}$
Soil Temp (ºF)						NO DATA					
VMC (%)											
Salinity index (mS/cm)											

Table F.2: Moisture and surface temperature readings collected on 23rd March 2021

Date: 3/23/2021											
West wall (north)											
		Air temp: 67.5 ºF			Air temp: 80.6 ºF						
		RH: 26.4%			RH: 22%						
Windy + Sunny		DP: 31.5 ºF			DP: 38.4 ºF						
		Time: 10:19am			11:18am		Recorded by: Alex Lim & Garrett				
MC	$W_{(0,6)}$	$W_{(2,6)}$	$W_{(4,6)}$	$W_{(6,6)}$	$W_{(8,6)}$	$W_{(10,6)}$	$W_{(12,6)}$	$W_{(14,6)}$	$W_{(16,6)}$	$W_{(18,6)}$	$W_{(20,6)}$
MC	133D	136D	125D	116D	120D	129D	132D	119D	102D	89D	123D
Sur Temp (ºF)	82.3	81.6	81.2	85.8	81.5	84.7	87	91.4	90.8	96.7	96.3
Surf. T Diff (ºF)	44	43.9	43.5	48.3	44.5	45.1	49.5	53.4	50.4	58.7	59.7
MC	$W_{(0,4)}$	$W_{(2,4)}$	$W_{(4,4)}$	$W_{(6,4)}$	$W_{(8,4)}$	$W_{(10,4)}$	$W_{(12,4)}$	$W_{(14,4)}$	$W_{(16,4)}$	$W_{(18,4)}$	$W_{(20,4)}$
MC	116D	137D	131D	142D	132D	120D	137D	112D	131D	104D	123D
Sur Temp (ºF)	81.7	76.4	80.3	83.2	88	88.6	89.3	87.4	85.9	94.8	93.3
Surf. T Diff (ºF)	45.3	38.8	41.9	46.1	50.4	49.3	52.3	48.6	48.5	56.4	54.9
MC	$W_{(0,2)}$	$W_{(2,2)}$	$W_{(4,2)}$	$W_{(6,2)}$	$W_{(8,2)}$	$W_{(10,2)}$	$W_{(12,2)}$	$W_{(14,2)}$	$W_{(16,2)}$	$W_{(18,2)}$	$W_{(20,2)}$
MC	142D	128D	128D	136D	133D	138D	124D	128D	120D	123D	120D
Sur Temp (ºF)	83.7	83.1	88.9	84.4	94.3	96.7	94.3	93.5	95	95.3	94.9
Surf. T Diff (ºF)	47.5	45	50.7	47.5	56	58.6	56.9	54.9	59.1	56.9	55
MC	$W_{(0,0)}$	$W_{(2,0)}$	$W_{(4,0)}$	$W_{(6,0)}$	$W_{(8,0)}$	$W_{(10,0)}$	$W_{(12,0)}$	$W_{(14,0)}$	$W_{(16,0)}$	$W_{(18,0)}$	$W_{(20,0)}$
MC	88D	120D	104D	96D	132D	86D	66D	81D	106D	66D	61D
Sur Temp (ºF)	96.9	97.8	96.6	99	101.9	107.3	105.2	106.5	106.8	101.5	113.3
Surf. T Diff (ºF)	59.5	59.3	59.8	61.8	71	70.1	67.4	69.1	69.3	63.4	74.7
Soil Temp (ºF)	$S_{(0,0.5)}$	$S_{(2,0.5)}$	$S_{(4,0.5)}$	$S_{(6,0.5)}$	$S_{(8,0.5)}$	$S_{(10,1)}$	$S_{(12,0.5)}$	$S_{(14,0.5)}$	$S_{(16,0.5)}$	$S_{(18,0.5)}$	$S_{(20,0.5)}$
Soil Temp (ºF)						NO DATA					
VMC (%)											
Salinity index (mS/cm)											
Soil Temp (ºF)	$S_{(0,3")}$	$S_{(2,3")}$	$S_{(4,3")}$	$S_{(6,3")}$	$S_{(8,3")}$	$S_{(10,3")}$	$S_{(12,3")}$	$S_{(14,3")}$	$S_{(16,3")}$	$S_{(18,3")}$	$S_{(20,3")}$
Soil Temp (ºF)						NO DATA					
VMC (%)											
Salinity index (mS/cm)											

Table F.3: Moisture and surface temperature readings collected on 23rd March 2021

Date: 3/23/2021											
West wall (south)											
		Air temp: 67.5 ºf		Air temp: 77.2 ºF							
		RH: 26.4%		RH: 23.5%							
Windy + Sunny		DP: 31.5 ºF		DP: 37 ºF							
		Time: 10:19am		11:00am		Recorded by: Alex Lim & Garrett					
MC	$W_{(0,6)}$	$W_{(2,6)}$	$W_{(4,6)}$	$W_{(6,6)}$	$W_{(8,6)}$	$W_{(10,6)}$	$W_{(12,6)}$	$W_{(14,6)}$	$W_{(16,6)}$	$W_{(18,6)}$	$W_{(20,6)}$
MC	138D	120D	104D	119D	127D	102D	124D	127D	112D	113D	131D
Sur Temp (ºF)	95.4	87.6	79	81.4	80	78	76.6	73.9	71.6	77.1	75.7
Surf. T Diff (ºF)	59.8	51.1	41.3	43.4	43.5	40	39.7	35.9	34.4	41.7	38
MC	$W_{(0,4)}$	$W_{(2,4)}$	$W_{(4,4)}$	$W_{(6,4)}$	$W_{(8,4)}$	$W_{(10,4)}$	$W_{(12,4)}$	$W_{(14,4)}$	$W_{(16,4)}$	$W_{(18,4)}$	$W_{(20,4)}$
MC	110D	117D	115D	110D	116D	119D	120D	116D	116D	107D	88D
Sur Temp (ºF)	99.7	95.8	94.9	96.8	90	90.1	93.5	91.2	88.7	87.9	90.1
Surf. T Diff (ºF)	63.4	60.9	59.6	59.1	54.1	52.1	55.2	55.5	52.3	51.7	52.4
MC	$W_{(0,2)}$	$W_{(2,2)}$	$W_{(4,2)}$	$W_{(6,2)}$	$W_{(8,2)}$	$W_{(10,2)}$	$W_{(12,2)}$	$W_{(14,2)}$	$W_{(16,2)}$	$W_{(18,2)}$	$W_{(20,2)}$
MC	145D	152D	130D	128D	138D	128D	131D	128D	120D	127D	152D
Sur Temp (ºF)	106.1	101	98	97.3	96.9	94.7	93.5	91.9	92.2	90.8	94.8
Surf. T Diff (ºF)	69.2	65.4	60.3	59.8	60.1	56.4	55.2	55.4	56.1	53.7	56.8
MC	$W_{(0,0)}$	$W_{(2,0)}$	$W_{(4,0)}$	$W_{(6,0)}$	$W_{(8,0)}$	$W_{(10,0)}$	$W_{(12,0)}$	$W_{(14,0)}$	$W_{(16,0)}$	$W_{(18,0)}$	$W_{(20,0)}$
MC	120D	110D	81D	85D	133D	128D	116D	81D	120D	134D	85D
Sur Temp (ºF)	113	111.4	108.4	106	106.1	105.9	108.3	101.3	103.3	101.4	100.6
Surf. T Diff (ºF)	77.2	75	71.8	69.2	68.9	68.9	70.8	63.1	66.3	65.9	61.9
Soil Temp (ºF)	$S_{(0,0.5)}$	$S_{(2,0.5)}$	$S_{(4,0.5)}$	$S_{(6,0.5)}$	$S_{(8,0.5)}$	$S_{(10,1)}$	$S_{(12,0.5)}$	$S_{(14,0.5)}$	$S_{(16,0.5)}$	$S_{(18,0.5)}$	$S_{(20,0.5)}$
Soil Temp (ºF)						NO DATA					
VMC (%)											
Salinity index											
Soil Temp (ºF)	$S_{(0,3")}$	$S_{(2,3")}$	$S_{(4,3")}$	$S_{(6,3")}$	$S_{(8,3")}$	$S_{(10,3")}$	$S_{(12,3")}$	$S_{(14,3")}$	$S_{(16,3")}$	$S_{(18,3")}$	$S_{(20,3")}$
Soil Temp (ºF)						NO DATA					
VMC (%)											
Salinity index (mS/cm)											

Table F.4: Moisture and surface temperature readings collected on 24th March 2021

North wall											
Date: 3/24/2021		Air temp: 66.3 ºF				Air temp: 75.7 ºF					
		RH: 37.2%				RH: 32.0%					
Overcast + Sunny		DP: 39.7ºF		Cloudy + overcast		DP: 44.5 ºF					
9" rain overnight		Time: 1:43pm		Few drops of rain		2:01pm		Recorded by: Alex Lim & Garrett			
MC	$W_{(0,6)}$	$W_{(2,6)}$	$W_{(4,6)}$	$W_{(6,6)}$	$W_{(8,6)}$	$W_{(10,6)}$	$W_{(12,6)}$	$W_{(14,6)}$	$W_{(16,6)}$	$W_{(18,6)}$	$W_{(20,6)}$
MC	119D	149D	142D	120D	136D	124D	131D	136D	96D	128D	116D
Sur Temp (ºF)	97.3	92.6	91.3	94.1	87.9	88.9	92.9	91.1	94.8	97.5	98.2
Surf. T Diff (ºF)	56	52.2	50.2	52.9	44.2	47.2	49.7	46.9	49.3	54.9	52.5
MC	$W_{(0,4)}$	$W_{(2,4)}$	$W_{(4,4)}$	$W_{(6,4)}$	$W_{(8,4)}$	$W_{(10,4)}$	$W_{(12,4)}$	$W_{(14,4)}$	$W_{(16,4)}$	$W_{(18,4)}$	$W_{(20,4)}$
MC	113D	131D	118D	120D	120D	112D	120D	126D	104D	120D	115D
Sur Temp (ºF)	98.3	99	93.9	91.9	91.5	85.6	91.8	90	88.8	94.8	96.1
Surf. T Diff (ºF)	56.7	58.1	52.4	50.8	48.7	43.4	48.9	45.4	42.4	51.7	50.7
MC	$W_{(0,2)}$	$W_{(2,2)}$	$W_{(4,2)}$	$W_{(6,2)}$	$W_{(8,2)}$	$W_{(10,2)}$	$W_{(12,2)}$	$W_{(14,2)}$	$W_{(16,2)}$	$W_{(18,2)}$	$W_{(20,2)}$
MC	132D	104D	138D	112D	131D	124D	105D	112D	112D	97D	112D
Sur Temp (ºF)	102.3	99	94.3	94.3	91.1	89.7	87.8	95.6	96.8	97	96.6
Surf. T Diff (ºF)	60.2	58.3	51.9	53.1	48.8	46.7	45.2	51.4	51.7	52.6	51.8
MC	$W_{(0,0)}$	$W_{(2,0)}$	$W_{(4,0)}$	$W_{(6,0)}$	$W_{(8,0)}$	$W_{(10,0)}$	$W_{(12,0)}$	$W_{(14,0)}$	$W_{(16,0)}$	$W_{(18,0)}$	$W_{(20,0)}$
MC	131D	116D	116D	120D	112D	112D	120D	112D	112D	112D	104D
Sur Temp (ºF)	109.1	104.9	101.2	102.3	97.4	95.2	95.1	101.9	100.5	101.8	104
Surf. T Diff (ºF)	67.4	63.6	61.2	61.2	55.5	52.4	52.3	59.8	46.4	55.3	59.5
Soil Temp (ºF)	$S_{(0,0.5)}$	$S_{(2,0.5)}$	$S_{(4,0.5)}$	$S_{(6,0.5)}$	$S_{(8,0.5)}$	$S_{(10,1)}$	$S_{(12,0.5)}$	$S_{(14,0.5)}$	$S_{(16,0.5)}$	$S_{(18,0.5)}$	$S_{(20,0.5)}$
Soil Temp (ºF)	68.9	-	70.4	-	70.8	-	71.5	-	71.7	-	72.2
VMC (%)	6.2	-	5.9	-	4.9	-	1.1 (5" only	-	2.7 (5" only	-	4.6
Salinity index (mS/cm)	0	-	0.02	-	0	-	0	-	0.02	-	0.03
Soil Temp (ºF)	$S_{(0,3'')}$	$S_{(2,3'')}$	$S_{(4,3'')}$	$S_{(6,3'')}$	$S_{(8,3'')}$	$S_{(10,3'')}$	$S_{(12,3'')}$	$S_{(14,3'')}$	$S_{(16,3'')}$	$S_{(18,3'')}$	$S_{(20,3'')}$
Soil Temp (ºF)	70	-	70.5	-	71.2	-	71.7	-	71.9	-	72.4
VMC (%)	6.5	-	6.9	-	5.5	-	4.6	-	6.3	-	5.2
Salinity index (mS/cm)	0.03	-	0.05	-	0.03	-	0.03	-	0.05	-	0

Table F.5: Moisture and surface temperature readings collected on 24th March 2021

Date: 3/24/2021											
West wall (north)		Air temp: 61.7 ºF			Air temp: 69.9 ºF						
		RH: 48.1 %			RH: 44 %						
Overcast, No wind		DP: 41.8 ºF			DP: 46.7 ºF						
9" rain overnight		Time: 10:22am			10:38am		Recorded by: Alex Lim & Garrett				
MC	$W_{(0,6)}$		$W_{(4,6)}$	$W_{(6,6)}$	$W_{(8,6)}$	$W_{(10,6)}$	$W_{(12,6)}$	$W_{(14,6)}$	$W_{(16,6)}$	$W_{(18,6)}$	$W_{(20,6)}$
MC	121D	130D	135D	137D	138D	136D	138D	138D	136D	137D	131D
Sur Temp (ºF)	60.2	66.1	66.2	67.9	64.9	68.2	71.2	76.8	74.9	80.9	84.3
Surf. T Diff (ºF)	17.3	22.4	21.4	24.2	21.2	25.4	27.2	31	29.5	33.7	39
MC	$W_{(0,4)}$	$W_{(2,4)}$	$W_{(4,4)}$	$W_{(6,4)}$	$W_{(8,4)}$	$W_{(10,4)}$	$W_{(12,4)}$	$W_{(14,4)}$	$W_{(16,4)}$	$W_{(18,4)}$	$W_{(20,4)}$
MC	129D	159D	145D	149D	152D	138D	142D	133D	145D	131D	138D
Sur Temp (ºF)	61.8	62.3	66.8	68.8	67.7	68.2	71.4	71.6	71.6	78.2	81.5
Surf. T Diff (ºF)	18.8	18.3	22.1	25.1	23.8	25.5	26.7	26.2	25.6	31.8	35.8
MC	$W_{(0,2)}$	$W_{(2,2)}$	$W_{(4,2)}$	$W_{(6,2)}$	$W_{(8,2)}$	$W_{(10,2)}$	$W_{(12,2)}$	$W_{(14,2)}$	$W_{(16,2)}$	$W_{(18,2)}$	$W_{(20,2)}$
MC	146D	136D	124D	142D	150D	151D	132D	142D	138D	142D	142D
Sur Temp (ºF)	62.5	64.1	68.9	66.7	70.2	68.8	70.4	71.6	74.5	76.3	80.4
Surf. T Diff (ºF)	18.1	20.5	24.2	22.5	26.6	25.8	25.9	26.4	28.1	30.2	34.6
MC	$W_{(0,0)}$	$W_{(2,0)}$	$W_{(4,0)}$	$W_{(6,0)}$	$W_{(8,0)}$	$W_{(10,0)}$	$W_{(12,0)}$	$W_{(14,0)}$	$W_{(16,0)}$	$W_{(18,0)}$	$W_{(20,0)}$
MC	182R	193R	175R	167D	187R	149D	112D	141D	120D	136D	143D
Sur Temp (ºF)	68	68.5	70.1	74	75.5	73	71.6	76.7	82.8	78.9	86
Surf. T Diff (ºF)	28.4	25.6	26.2	28.2	32.6	28.9	28.1	32	36.6	34.8	39.5
Soil Temp (ºF)	$S_{(0,0.5)}$	$S_{(2,0.5)}$	$S_{(4,0.5)}$	$S_{(6,0.5)}$	$S_{(8,0.5)}$	$S_{(10,1)}$	$S_{(12,0.5)}$	$S_{(14,0.5)}$	$S_{(16,0.5)}$	$S_{(18,0.5)}$	$S_{(20,0.5)}$
Soil Temp (ºF)	70.1	-	70.1	-	70.7	-	70.3	-	70.2	-	70.2
VMC (%)	4.5	-	3.3	-	1.8	-	1.4	-	1.5	-	5.7
Salinity index (mS/cm)	0	-	0.03	-	0	-	0	-	0	-	0
Soil Temp (ºF)	$S_{(0,3")}$	$S_{(2,3")}$	$S_{(4,3")}$	$S_{(6,3")}$	$S_{(8,3")}$	$S_{(10,3")}$	$S_{(12,3")}$	$S_{(14,3")}$	$S_{(16,3")}$	$S_{(18,3")}$	$S_{(20,3")}$
Soil Temp (ºF)	70.2	-	72.1	-	70.4	-	70.4	-	70.2	-	70.3
VMC (%)	5.6	-	3.9	-	5.2	-	2.6	-	6	-	3.8
Salinity index (mS/cm)	0.03	-	0	-	0	-	0	-	0	-	0

Table F.6: Moisture and surface temperature readings collected on 24th March 2021

West wall (south)											
Date: 3/24/2021		Air temp: 59.6 ºF			Air temp: 60 ºF						
		RH: 51.8%			RH: 50%						
Overcast, No wind		DP: 41.9 ºF			DP: 42.0 ºF						
9" rain overnight		Time: 9:43am			10:00am		Recorded by: Alex Lim & Garrett				
MC	$W_{(0,6)}$	$W_{(2,6)}$	$W_{(4,6)}$	$W_{(6,6)}$	$W_{(8,6)}$	$W_{(10,6)}$	$W_{(12,6)}$	$W_{(14,6)}$	$W_{(16,6)}$	$W_{(18,6)}$	$W_{(20,6)}$
MC	154D	138D	145D	138D	156D	136D	145D	142D	136D	143D	167D
Sur Temp (ºF)	64.6	64.5	61.6	62.5	63	61.3	59.7	60.5	59.8	60	57.8
Surf. T Diff (ºF)	19.2	16.1	16	15.2	15.6	14.8	14	13	12.8	13.5	12
MC	$W_{(0,4)}$	$W_{(2,4)}$	$W_{(4,4)}$	$W_{(6,4)}$	$W_{(8,4)}$	$W_{(10,4)}$	$W_{(12,4)}$	$W_{(14,4)}$	$W_{(16,4)}$	$W_{(18,4)}$	$W_{(20,4)}$
MC	142D	136D	142D	136D	143D	145D	142D	142D	138D	131D	136D
Sur Temp (ºF)	63.9	63.8	64.5	63.4	61.5	61.2	61.5	61.1	59.9	60.2	58.9
Surf. T Diff (ºF)	18	15.7	19	15.8	14.4	14.4	16.1	13.1	12.2	13.2	12.9
MC	$W_{(0,2)}$	$W_{(2,2)}$	$W_{(4,2)}$	$W_{(6,2)}$	$W_{(8,2)}$	$W_{(10,2)}$	$W_{(12,2)}$	$W_{(14,2)}$	$W_{(16,2)}$	$W_{(18,2)}$	$W_{(20,2)}$
MC	212W	229W	202W	163D	230W	195R	177R	177R	172R	187R	239W
Sur Temp (ºF)	63.8	65	64.7	64.1	64.1	63.3	62.1	62.7	62.7	61.4	61.5
Surf. T Diff (ºF)	17.6	17.9	19.1	17.4	16.9	16.2	16.4	15.7	14.5	14.4	16.9
MC	$W_{(0,0)}$	$W_{(2,0)}$	$W_{(4,0)}$	$W_{(6,0)}$	$W_{(8,0)}$	$W_{(10,0)}$	$W_{(12,0)}$	$W_{(14,0)}$	$W_{(16,0)}$	$W_{(18,0)}$	$W_{(20,0)}$
MC	217W	155D	168D	174R	210W	181R	197R	167D	161D	178R	167D
Sur Temp (ºF)	65.7	68.6	69.7	69.2	68.5	68.5	68.5	67.6	67.2	66.6	66.4
Surf. T Diff (ºF)	21.3	23	23.4	24.5	22.3	22.5	23.5	122.7	19.9	18.4	21.4
Soil Temp (ºF)	$S_{(0,0.5)}$	$S_{(2,0.5)}$	$S_{(4,0.5)}$	$S_{(6,0.5)}$	$S_{(8,0.5)}$	$S_{(10,1)}$	$S_{(12,0.5)}$	$S_{(14,0.5)}$	$S_{(16,0.5)}$	$S_{(18,0.5)}$	$S_{(20,0.5)}$
Soil Temp (ºF)	66.2	-	67.1	-	68	-	72	-	71.8	-	70.7
VMC (%)	3.2	-	3.5	-	6.9	-	1.2	-	4.4	-	3.8
Salinity index (mS/cm)	0	-	0	-	0	-	0	-	0	-	0
Soil Temp (ºF)	$S_{(0,3")}$	$S_{(2,3")}$	$S_{(4,3")}$	$S_{(6,3")}$	$S_{(8,3")}$	$S_{(10,3")}$	$S_{(12,3")}$	$S_{(14,3")}$	$S_{(16,3")}$	$S_{(18,3")}$	$S_{(20,3")}$
Soil Temp (ºF)	66.3	-	67.6	-	68.4	-	70.9	-	71.2	-	70.6
VMC (%)	4.6	-	5.3	-	3.4	-	6.3	-	6.6	-	4.3
Salinity index (mS/cm)	0	-	0.02	-	0	-	0	-	0	-	0

Table F.7: Moisture and surface temperature readings collected on 25th March 2021

Date: 3/25/2021											
North wall		Air temp: 70.1 ºF		Air temp: 76.3 ºF		Air temp: 73.4 ºF					
		RH: 24.3 %		RH: 22.2%		RH: 26.8%					
Overcast + windy		DP: 32.7 ºF		DP: 36.3 ºF		DP: 36.2 ºF					
		Time: 1:35pm		2:30pm		2:00pm		Recorded by: Alex Lim & Garrett			
MC	$W_{(0,6)}$	$W_{(2,6)}$	$W_{(4,6)}$	$W_{(6,6)}$	$W_{(8,6)}$	$W_{(10,6)}$	$W_{(12,6)}$	$W_{(14,6)}$	$W_{(16,6)}$	$W_{(18,6)}$	$W_{(20,6)}$
MC	104D	142D	131D	81D	105D	81D	120D	124D	81D	96D	110D
Sur Temp (ºF)	84.5	78.4	76.6	81.2	74.3	71.8	71.6	70.9	65.6	67.2	66.3
Surf. T Diff (ºF)	44.6	38.6	34.5	43.1	36.9	32.4	30.2	30.6	27.1	28.3	29.2
MC	$W_{(0,4)}$	$W_{(2,4)}$	$W_{(4,4)}$	$W_{(6,4)}$	$W_{(8,4)}$	$W_{(10,4)}$	$W_{(12,4)}$	$W_{(14,4)}$	$W_{(16,4)}$	$W_{(18,4)}$	$W_{(20,4)}$
MC	88D	120D	117D	61D	65D	96D	120D	73D	104D	96D	70D
Sur Temp (ºF)	84.9	88.5	78.6	76.7	69.7	68.3	70.5	68.2	64.6	67.2	62.5
Surf. T Diff (ºF)	45.6	46.1	41.9	39.5	33.2	29.6	31.3	30.2	27.1	26.8	24.2
MC	$W_{(0,2)}$	$W_{(2,2)}$	$W_{(4,2)}$	$W_{(6,2)}$	$W_{(8,2)}$	$W_{(10,2)}$	$W_{(12,2)}$	$W_{(14,2)}$	$W_{(16,2)}$	$W_{(18,2)}$	$W_{(20,2)}$
MC	104D	96D	128D	96D	102D	92D	92D	112D	112D	77D	104D
Sur Temp (ºF)	88.4	88.2	82.3	79.4	75.5	75.2	71.6	71.6	69.9	70.4	67.7
Surf. T Diff (ºF)	51.3	49.8	43.3	41.7	37.7	37.3	32.6	32.9	31.2	30.2	27.5
MC	$W_{(0,0)}$	$W_{(2,0)}$	$W_{(4,0)}$	$W_{(6,0)}$	$W_{(8,0)}$	$W_{(10,0)}$	$W_{(12,0)}$	$W_{(14,0)}$	$W_{(16,0)}$	$W_{(18,0)}$	$W_{(20,0)}$
MC	112D	73D	92D	100D	104D	81D	96D	73D	89D	81D	88D
Sur Temp (ºF)	95.6	91.6	88.3	85.3	79.4	80.5	76.4	79.3	75.1	74.6	71.6
Surf. T Diff (ºF)	55.4	52.7	50.1	47.8	42.7	42.4	36.8	41.7	34.6	35.9	31.2
Soil Temp (ºF)	$S_{(0,0.5)}$	$S_{(2,0.5)}$	$S_{(4,0.5)}$	$S_{(6,0.5)}$	$S_{(8,0.5)}$	$S_{(10,1)}$	$S_{(12,0.5)}$	$S_{(14,0.5)}$	$S_{(16,0.5)}$	$S_{(18,0.5)}$	$S_{(20,0.5)}$
Soil Temp (ºF)	83.3	-	83.5	-	82.6	-	82.4	-	82.1	-	81.8
VMC (%)	6	-	4	-	4.4	-	4.9	-	4.1	-	3.9
Salinity index (mS/cm)	0	-	0	-	0	-	0	-	0	-	0
Soil Temp (ºF)	$S_{(0,3")}$	$S_{(2,3")}$	$S_{(4,3")}$	$S_{(6,3")}$	$S_{(8,3")}$	$S_{(10,3")}$	$S_{(12,3")}$	$S_{(14,3")}$	$S_{(16,3")}$	$S_{(18,3")}$	$S_{(20,3")}$
Soil Temp (ºF)	83.7	-	83.1	-	82.9	-	82.5	-	82.2	-	81.6
VMC (%)	6.4	-	4.8	-	4.9	-	9.1	-	5.1	-	4.6
Salinity index (mS/cm)	0.1	-	0	-	0	-	0	-	0	-	0

Table F.8: Moisture and surface temperature readings collected on 25th March 2021

Date: 3/25/2021											
West wall (north)		Air temp: 74.9 ºF			Air temp: 66.5 ºF						
		RH: 27.8%			RH: 29.4%						
		DP: 39.7 ºF			DP: 34.1 ºF						
		Time: 11:00am			11:23am		Recorded by: Alex Lim & Garrett				
MC	$W_{(0,6)}$	$W_{(2,6)}$	$W_{(4,6)}$	$W_{(6,6)}$	$W_{(8,6)}$	$W_{(10,6)}$	$W_{(12,6)}$	$W_{(14,6)}$	$W_{(16,6)}$	$W_{(18,6)}$	$W_{(20,6)}$
MC	140D	128D	136D	133D	130D	132D	129D	131D	124D	131D	129D
Sur Temp (ºF)	71.6	75.1	70.8	73.6	69.8	71.6	71.6	77.3	74.2	77	75.8
Surf. T Diff (ºF)	33.5	37.2	34.8	36.5	32.3	34.3	34.6	40.1	37.2	40.6	40.2
MC	$W_{(0,4)}$	$W_{(2,4)}$	$W_{(4,4)}$	$W_{(6,4)}$	$W_{(8,4)}$	$W_{(10,4)}$	$W_{(12,4)}$	$W_{(14,4)}$	$W_{(16,4)}$	$W_{(18,4)}$	$W_{(20,4)}$
MC	121D	142D	124D	136D	134D	128D	134D	117D	133D	112D	112D
Sur Temp (ºF)	71.6	69.8	70.6	71.6	71.6	73	74.3	71.6	71.6	76.5	71.6
Surf. T Diff (ºF)	34.4	32.6	34.2	34.5	34.8	35.8	37.5	34.4	34.2	40.3	35.9
MC	$W_{(0,2)}$	$W_{(2,2)}$	$W_{(4,2)}$	$W_{(6,2)}$	$W_{(8,2)}$	$W_{(10,2)}$	$W_{(12,2)}$	$W_{(14,2)}$	$W_{(16,2)}$	$W_{(18,2)}$	$W_{(20,2)}$
MC	139D	132D	104D	131D	136D	133D	128D	131D	132D	131D	120D
Sur Temp (ºF)	71.6	72.6	76.9	71.6	78.4	78	77	77	77.1	75.7	71.6
Surf. T Diff (ºF)	35.2	35.9	40.4	34	41.8	41.4	40	39.5	39.7	38.6	35.8
MC	$W_{(0,0)}$	$W_{(2,0)}$	$W_{(4,0)}$	$W_{(6,0)}$	$W_{(8,0)}$	$W_{(10,0)}$	$W_{(12,0)}$	$W_{(14,0)}$	$W_{(16,0)}$	$W_{(18,0)}$	$W_{(20,0)}$
MC	112D	135D	136D	159D	152D	151D	138D	135D	102D	120D	145D
Sur Temp (ºF)	80	83.8	84.4	84.9	88	87.5	85.6	84.2	86.7	82.2	83.3
Surf. T Diff (ºF)	43.6	47.3	47.3	48.4	50.8	51.3	48.4	46.9	49.2	45.5	47.6
Soil Temp (ºF)	$S_{(0,0.5)}$	$S_{(2,0.5)}$	$S_{(4,0.5)}$	$S_{(6,0.5)}$	$S_{(8,0.5)}$	$S_{(10,1)}$	$S_{(12,0.5)}$	$S_{(14,0.5)}$	$S_{(16,0.5)}$	$S_{(18,0.5)}$	$S_{(20,0.5)}$
Soil Temp (ºF)	NO DATA										
VMC (%)											
Salinity index (mS/cm)											
Soil Temp (ºF)	$S_{(0,3")}$	$S_{(2,3")}$	$S_{(4,3")}$	$S_{(6,3")}$	$S_{(8,3")}$	$S_{(10,3")}$	$S_{(12,3")}$	$S_{(14,3")}$	$S_{(16,3")}$	$S_{(18,3")}$	$S_{(20,3")}$
Soil Temp (ºF)	NO DATA										
VMC (%)											
Salinity index (mS/cm)											

Table F.9: Moisture and surface temperature readings collected on 25th March 2021

Date: 3/25/2021											
West wall (south)		Air temp: 65.9 ºF		Air temp: 74.2 ºF		Air temp: 67.5 ºF					
		RH: 41.4%		RH: 32%		RH: 28.9%					
Windy + overcast		DP: 41.6 ºF		DP: 42.9 ºF		DP: 34.7 ºF					
		Time: 9:47am		10:05am		10:51am		Recorded by: Alex Lim & Garrett			
MC	$W_{(0,6)}$	$W_{(2,6)}$	$W_{(4,6)}$	$W_{(6,6)}$	$W_{(8,6)}$	$W_{(10,6)}$	$W_{(12,6)}$	$W_{(14,6)}$	$W_{(16,6)}$	$W_{(18,6)}$	$W_{(20,6)}$
MC	134D	135D	131D	160D	144D	149D	128D	145D	120D	120D	119D
Sur Temp (ºF)	95.2	94.3	88.6	94.4	96.7	89	91	92.4	88.9	91.9	89.4
Surf. T Diff (ºF)	51.4	48.2	42.3	49	54.4	44.7	46.8	49.3	46.1	47.2	45.3
MC	$W_{(0,4)}$	$W_{(2,4)}$	$W_{(4,4)}$	$W_{(6,4)}$	$W_{(8,4)}$	$W_{(10,4)}$	$W_{(12,4)}$	$W_{(14,4)}$	$W_{(16,4)}$	$W_{(18,4)}$	$W_{(20,4)}$
MC	131D	128D	138D	136D	131D	132D	131D	124D	125D	127D	116D
Sur Temp (ºF)	91.1	90	96.2	93.4	90.4	93.6	94.9	96	92.5	93.2	94
Surf. T Diff (ºF)	47.6	45.5	50.9	45.9	46.4	52.7	51.8	53.9	49.6	47.7	49.2
MC	$W_{(0,2)}$	$W_{(2,2)}$	$W_{(4,2)}$	$W_{(6,2)}$	$W_{(8,2)}$	$W_{(10,2)}$	$W_{(12,2)}$	$W_{(14,2)}$	$W_{(16,2)}$	$W_{(18,2)}$	$W_{(20,2)}$
MC	214W	191R	164D	164D	186D	168D	149D	130D	149D	162D	156D
Sur Temp (ºF)	92.8	96.4	98.5	98	96.2	99.1	96.3	96.9	97.8	95.8	97.7
Surf. T Diff (ºF)	47.7	51.1	53.4	52	52.3	57.4	52.8	55.8	54.1	51.7	54.6
MC	$W_{(0,0)}$	$W_{(2,0)}$	$W_{(4,0)}$	$W_{(6,0)}$	$W_{(8,0)}$	$W_{(10,0)}$	$W_{(12,0)}$	$W_{(14,0)}$	$W_{(16,0)}$	$W_{(18,0)}$	$W_{(20,0)}$
MC	166D	131D	131D	149D	123D	131D	145D	116D	88D	124D	96D
Sur Temp (ºF)	103.6	103.3	105.1	106.9	107.9	108.5	109.9	104.4	105.5	102.2	101.4
Surf. T Diff (ºF)	58.4	57.6	59	60.7	63.9	66.2	66.4	59.7	60.4	57.8	58
Soil Temp (ºF)	$S_{(0,0.5)}$	$S_{(2,0.5)}$	$S_{(4,0.5)}$	$S_{(6,0.5)}$	$S_{(8,0.5)}$	$S_{(10,1)}$	$S_{(12,0.5)}$	$S_{(14,0.5)}$	$S_{(16,0.5)}$	$S_{(18,0.5)}$	$S_{(20,0.5)}$
Soil Temp (ºF)	76.2	-	76.2	-	77.4	-	77.9	-	78.6	-	79.4
VMC (%)	2.9	-	3.7	-	7.6	-	3.8	-	4.7	-	4
Salinity index (mS/cm)	0.02	-	0	-	0	-	0	-	0	-	0
Soil Temp (ºF)	$S_{(0,3")}$	$S_{(2,3")}$	$S_{(4,3")}$	$S_{(6,3")}$	$S_{(8,3")}$	$S_{(10,3")}$	$S_{(12,3")}$	$S_{(14,3")}$	$S_{(16,3")}$	$S_{(18,3")}$	$S_{(20,3")}$
Soil Temp (ºF)	76.1	-	76.9	-	77.6	-	78.4	-	79.2	-	79
VMC (%)	4.5	-	5.2	-	5.6	-	2.8	-	5.9	-	4.2
Salinity index (mS/cm)	0.02	-	0	-	0	-	0	-	0.02	-	0

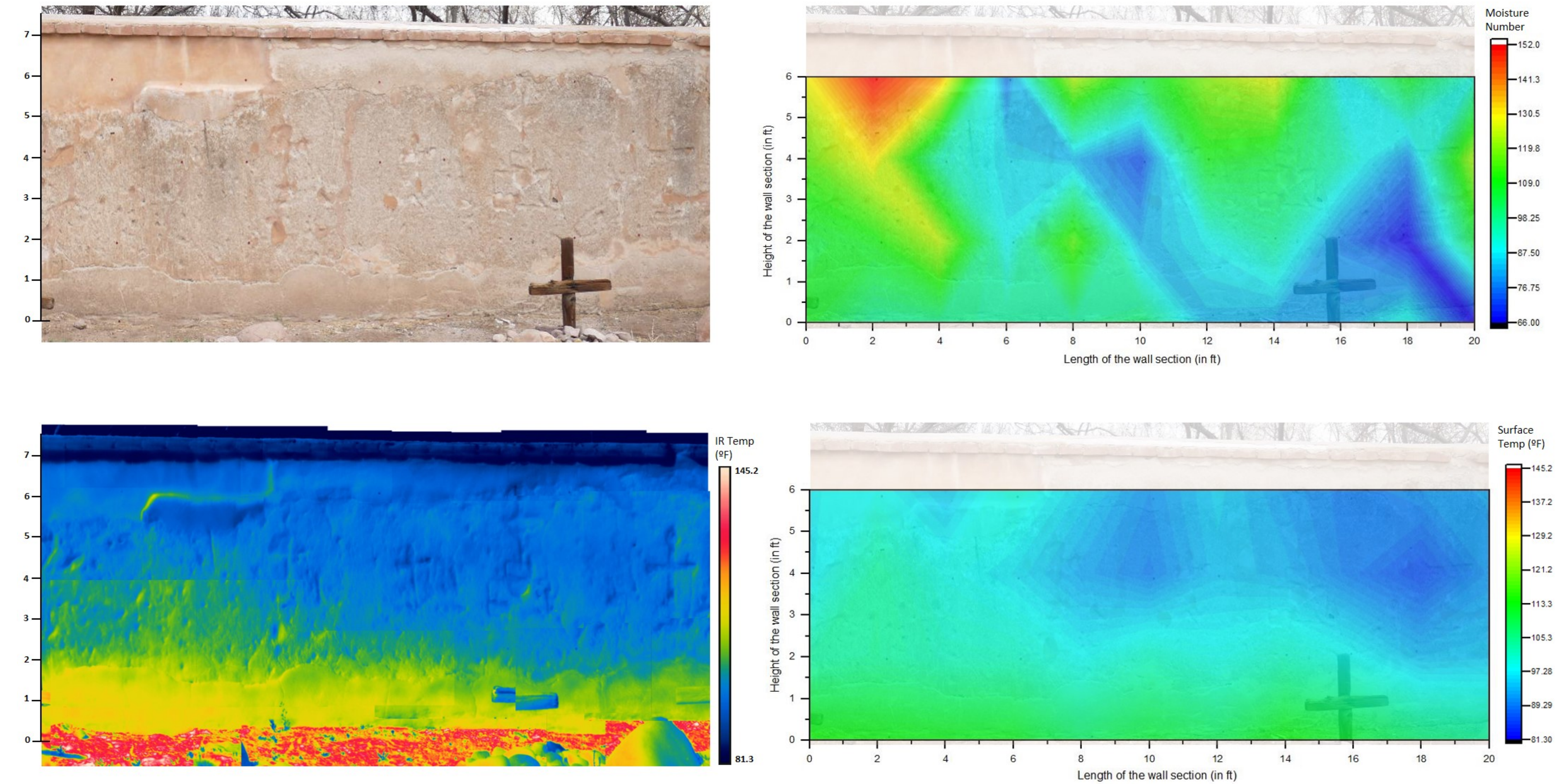


Figure F.1: (Clockwise starting from top left) Image of south-facing north wall section, moisture meter readings contour plot, surface temperature readings contour plot and thermal image. The moisture and surface temperature contour plots (on the right side) have readings up to a height of six feet from ground whereas the left images have the entire wall section.

Conditions: This data set belongs to the south-facing north wall section taken on 23rd March 2021 from 1:43pm to 1:55pm. While taking the readings the air temperature varied from 73.9 ºF to 78.2 ºF, the relative humidity varied from 22.2% to 20% and the Dew point varied from 33 ºF to 35.2 ºF. The overall condition was sunny + windy. No soil temperature and moisture data were collected for this case.

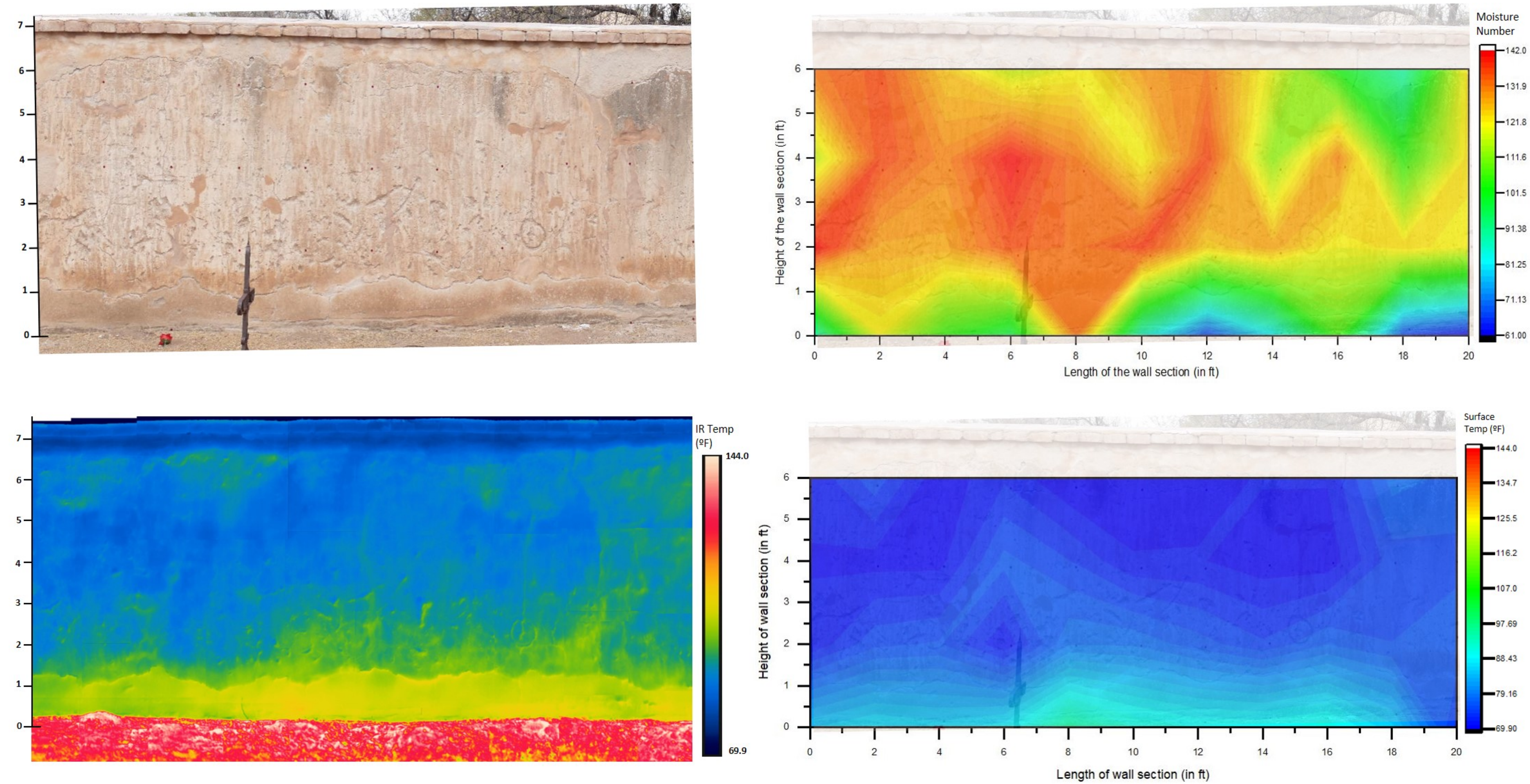


Figure F.2: (Clockwise starting from top left) Image of east-facing west wall section towards the north end, moisture meter readings contour plot, surface temperature readings contour plot and thermal image. The moisture and surface temperature contour plots (on the right side) have readings up to a height of six feet from ground whereas the left images have the entire wall section.

Conditions: This data set belongs to the east-facing west wall section towards the north end taken on 23rd March 2021 from 10:19am to 11:18am. While taking the readings the air temperature varied from 67.5 ºF to 80.6 ºF, the relative humidity varied from 26.4% to 22% and the Dew point varied from 31.5 ºF to 38.4 ºF. The overall condition was sunny + windy. No soil temperature and moisture data were collected for this case.

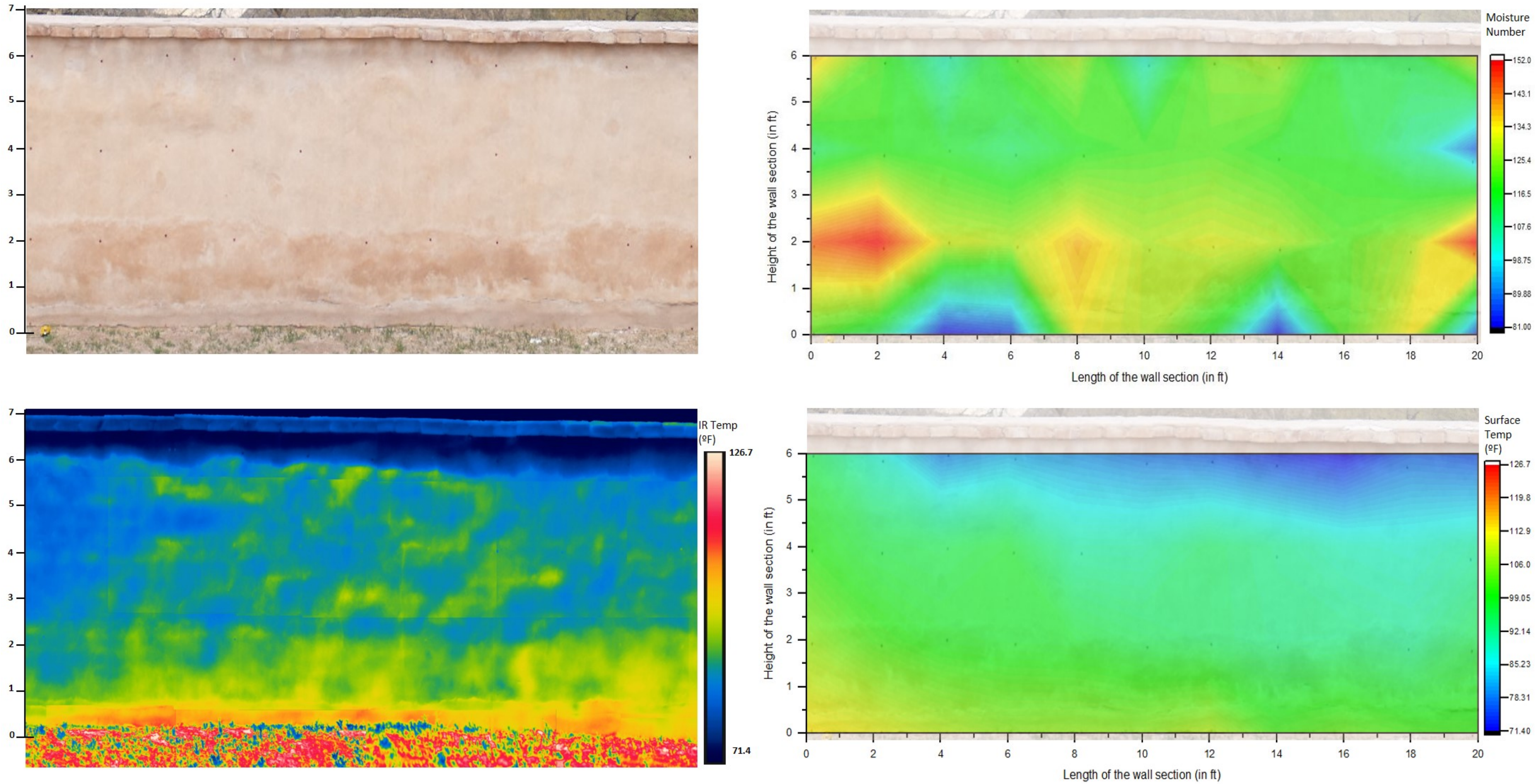


Figure F.3: (Clockwise starting from top left) Image of east-facing west wall section towards the south end, moisture meter readings contour plot, surface temperature readings contour plot and thermal image. The moisture and surface temperature contour plots (on the right side) have readings up to a height of six feet from ground whereas the left images have the entire wall section.

Conditions: This data set belongs to the east-facing west wall section towards the south end taken on 23rd March 2021 from 10:19am to 11:00am. While taking the readings the air temperature varied from 67.5 ºF to 77.2 ºF, the relative humidity varied from 26.4% to 23.5% and the Dew point varied from 31.5 ºF to 37 ºF. The overall condition was sunny + windy. No soil temperature and moisture data were collected for this case.

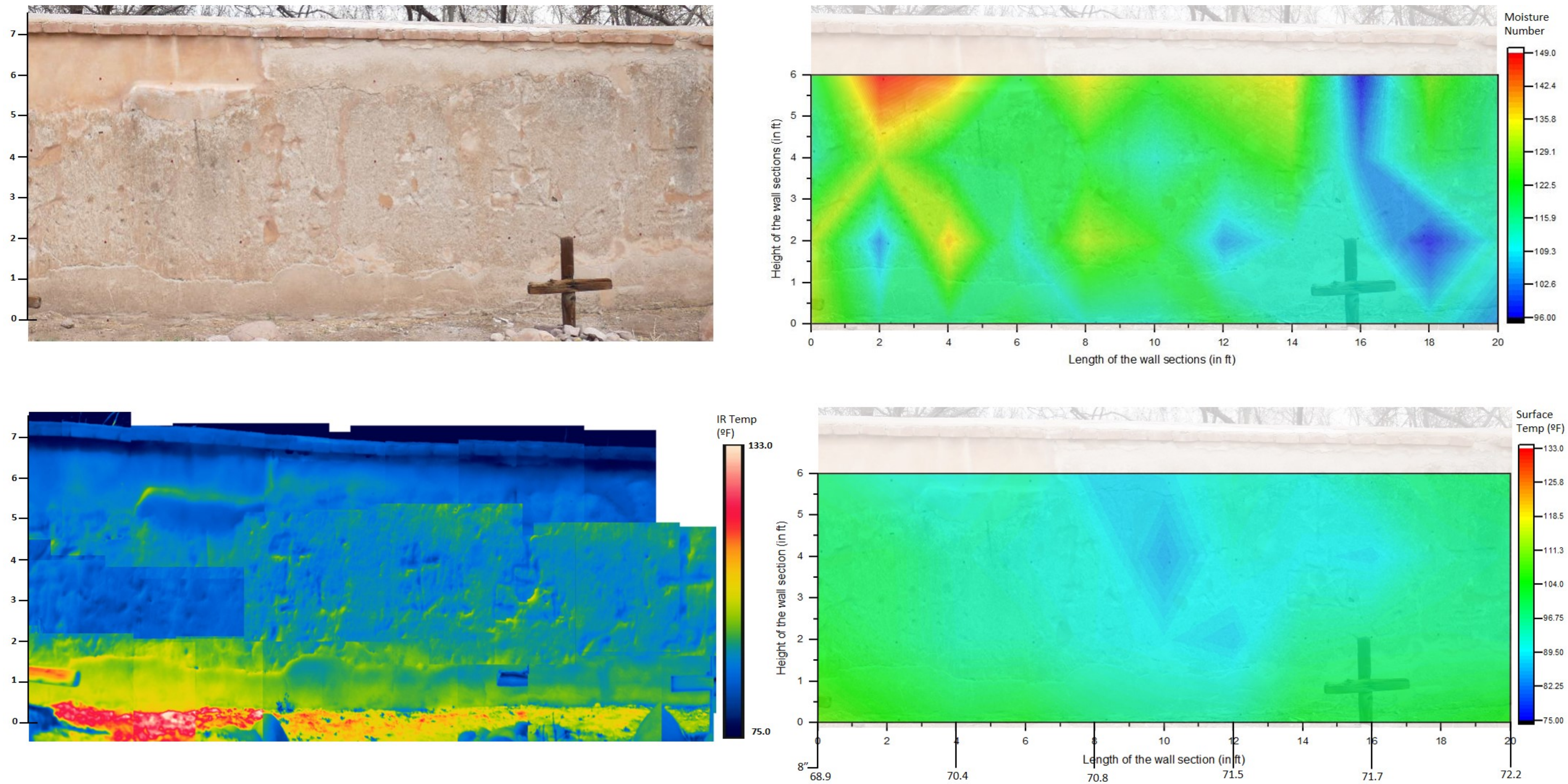


Figure F.4: (Clockwise starting from top left) Image of south-facing north wall section, moisture meter readings contour plot, surface temperature readings contour plot and thermal image. The moisture and surface temperature contour plots (on the right side) have readings up to a height of six feet from ground whereas the left images have the entire wall section.

Conditions: This data set belongs to the south-facing north wall section taken on 24th March 2021 from 1:43pm to 2:01pm. While taking the readings the air temperature varied from 66.3 ºF to 75.7 ºF, the relative humidity varied from 37.2% to 32% and the Dew point varied from 39.7 ºF to 44.5 ºF. The overall condition changed from sunny to cloudy with an overcast the entire time. There was an overnight rain event of 9" on the previous day. The surface temperature plot also shows the soil temperature (at a depth of 8 inch) in front of the wall, which has lower or similar temperature as the base of the wall.

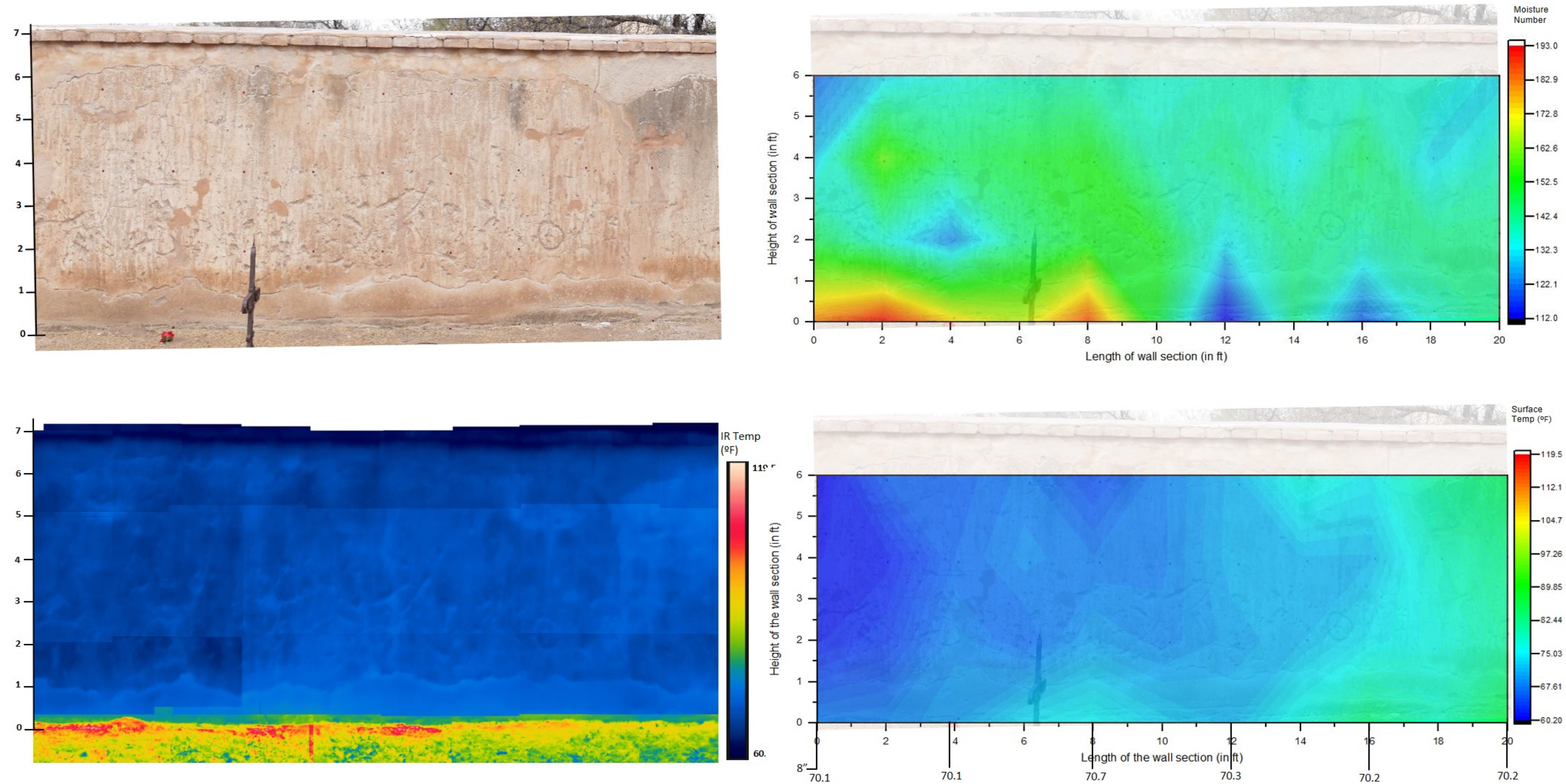


Figure F.5: (Clockwise starting from top left) Image of east-facing west wall section towards the north end, moisture meter readings contour plot, surface temperature readings contour plot and thermal image. The moisture and surface temperature contour plots (on the right side) have readings up to a height of six feet from ground whereas the left images have the entire wall section.

Conditions: This data set belongs to the east-facing west wall section towards the north end taken on 24th March 2021 from 10:22am to 10:38am. While taking the readings the air temperature varied from 61.7 ºF to 69.9 ºF, the relative humidity varied from 48.1% to 44% and the Dew point varied from 41.8 ºF to 46.7 ºF. There was overcast with no wind the entire time. There was an overnight rain event of 9" on the previous day. The surface temperature plot also shows the soil temperature (at a depth of 8 inch) in front of the wall, which has lower or similar temperature as the base of the wall.

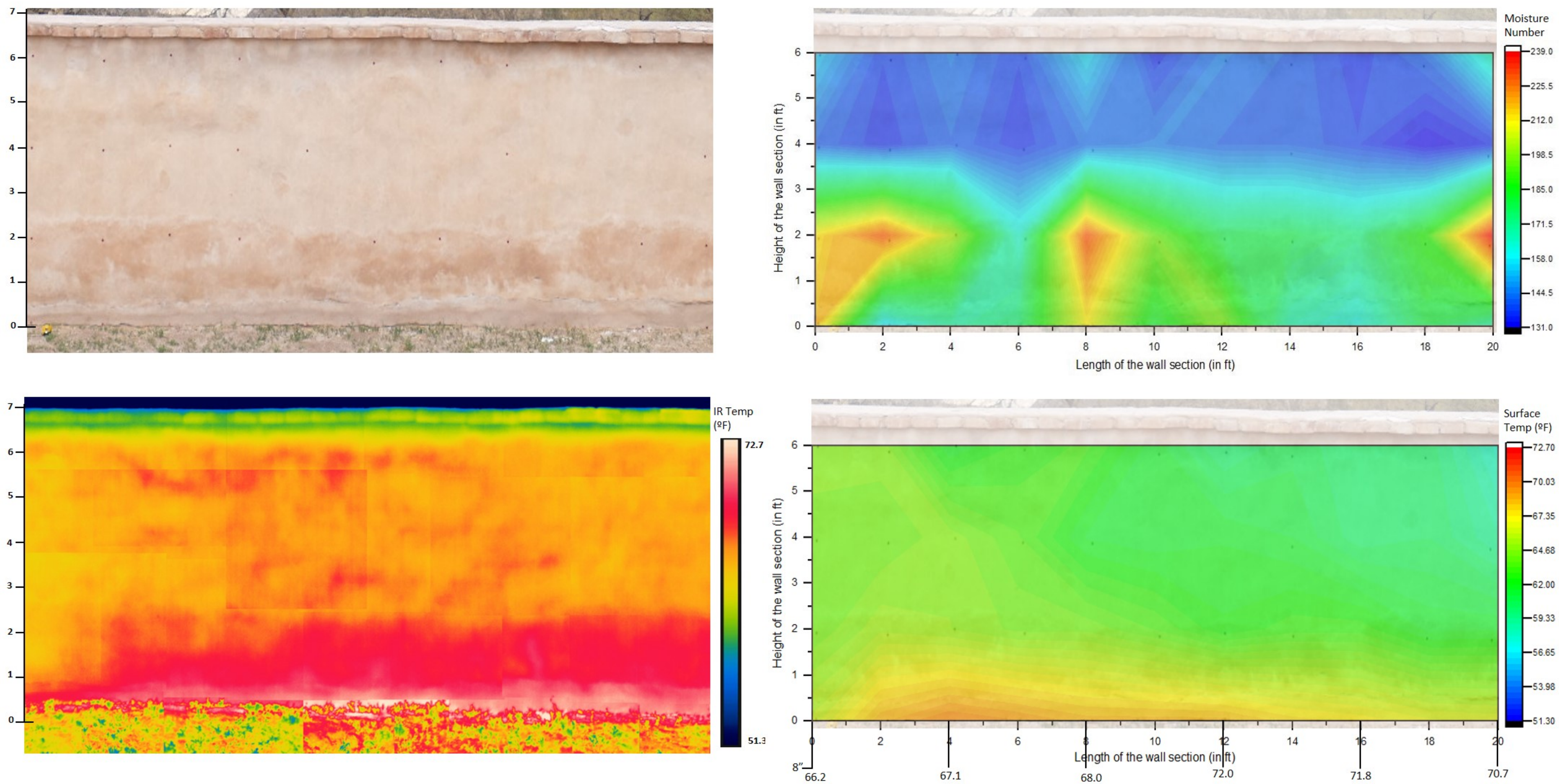


Figure F.6: (Clockwise starting from top left) Image of east-facing west wall section towards the south end, moisture meter readings contour plot, surface temperature readings contour plot and thermal image. The moisture and surface temperature contour plots (on the right side) have readings up to a height of six feet from ground whereas the left images have the entire wall section.

Conditions: This data set belongs to the east-facing west wall section towards the south end taken on 24th March 2021 from 9:43am to 10:00am. While taking the readings the air temperature varied from 59.6 ºF to 60 ºF, the relative humidity varied from 51.8% to 50% and the Dew point varied from 41.9 ºF to 42 ºF. There was overcast with no wind the entire time. There was an overnight rain event of 9" on the previous day. The surface temperature plot also shows the soil temperature (at a depth of 8 inch) in front of the wall, which has lower or similar temperature as the base of the wall.

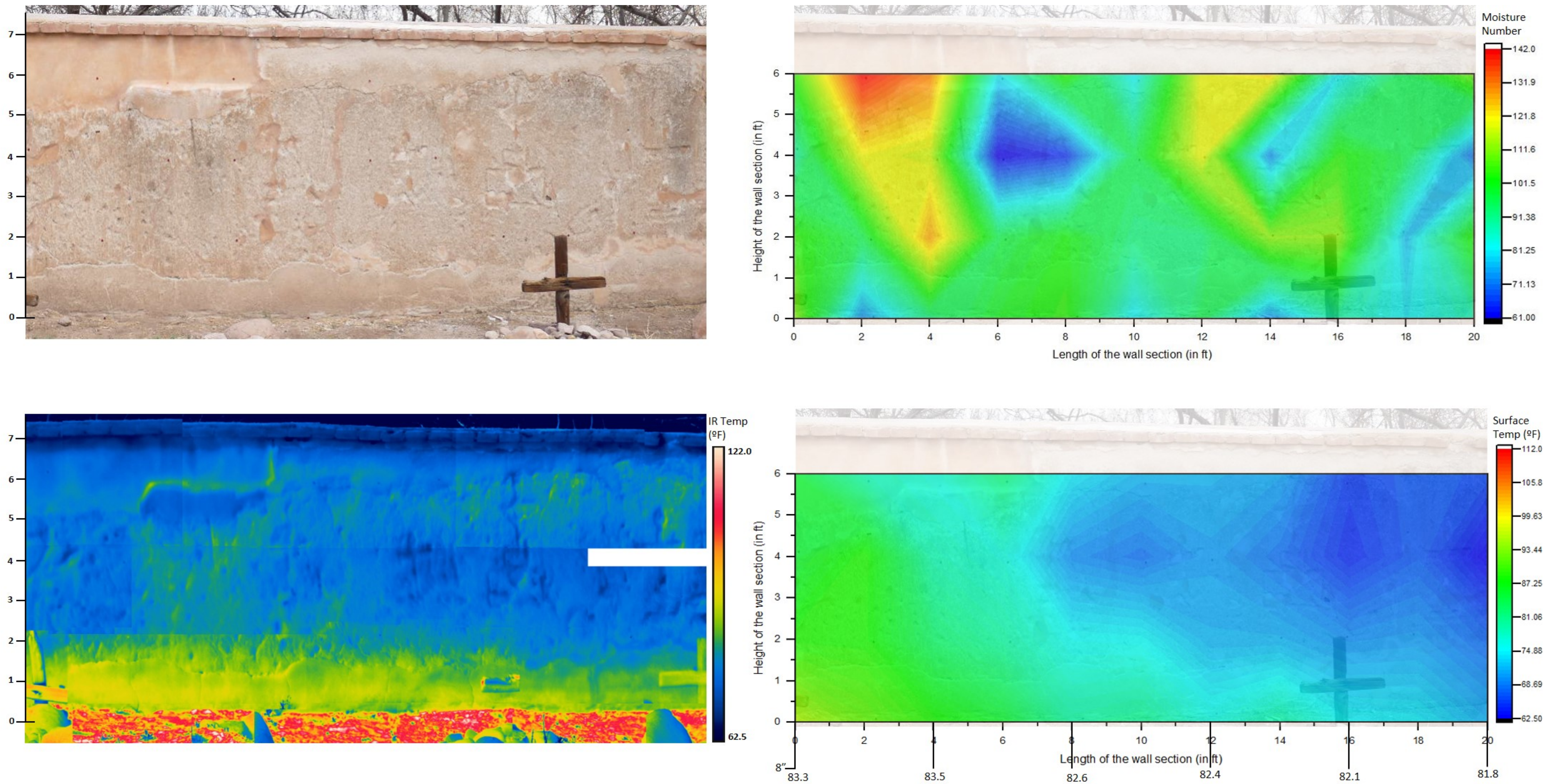


Figure F.7: (Clockwise starting from top left) Image of south-facing north wall section, moisture meter readings contour plot, surface temperature readings contour plot and thermal image. The moisture and surface temperature contour plots (on the right side) have readings up to a height of six feet from ground whereas the left images have the entire wall section.

Conditions: This data set belongs to the south-facing north wall section taken on 25th March 2021 from 1:35pm to 2:30pm. While taking the readings the air temperature varied from 70.1 ºF to 76.3 ºF, the relative humidity varied from 24.3% to 22.2% and the Dew point varied from 32.7 ºF to 36.3 ºF. There was overcast + windy the entire time. The surface temperature plot also shows the soil temperature (at a depth of 8 inch) in front of the wall, which has lower or similar temperature as the base of the wall.

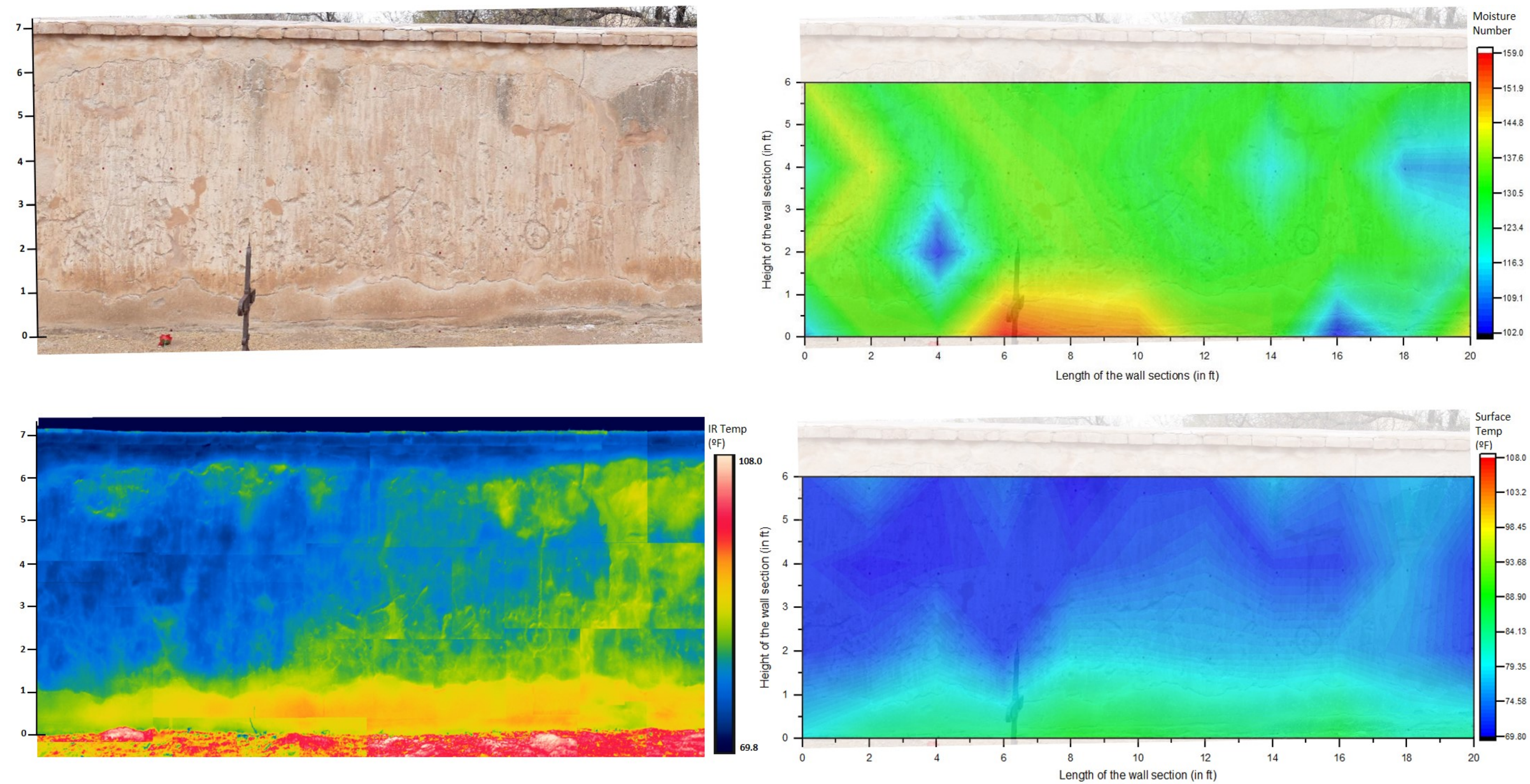


Figure F.8: (Clockwise starting from top left) Image of east-facing west wall section towards the north end, moisture meter readings contour plot, surface temperature readings contour plot and thermal image. The moisture and surface temperature contour plots (on the right side) have readings up to a height of six feet from ground whereas the left images have the entire wall section.

Conditions: This data set belongs to the east-facing west wall section towards the north end taken on 25th March 2021 from 11:00am to 11:23am. While taking the readings the air temperature varied from 74.9 ºF to 66.5 ºF, the relative humidity varied from 27.8% to 29.4% and the Dew point varied from 39.7 ºF to 34.1 ºF. No soil temperature and moisture data were collected for this case.

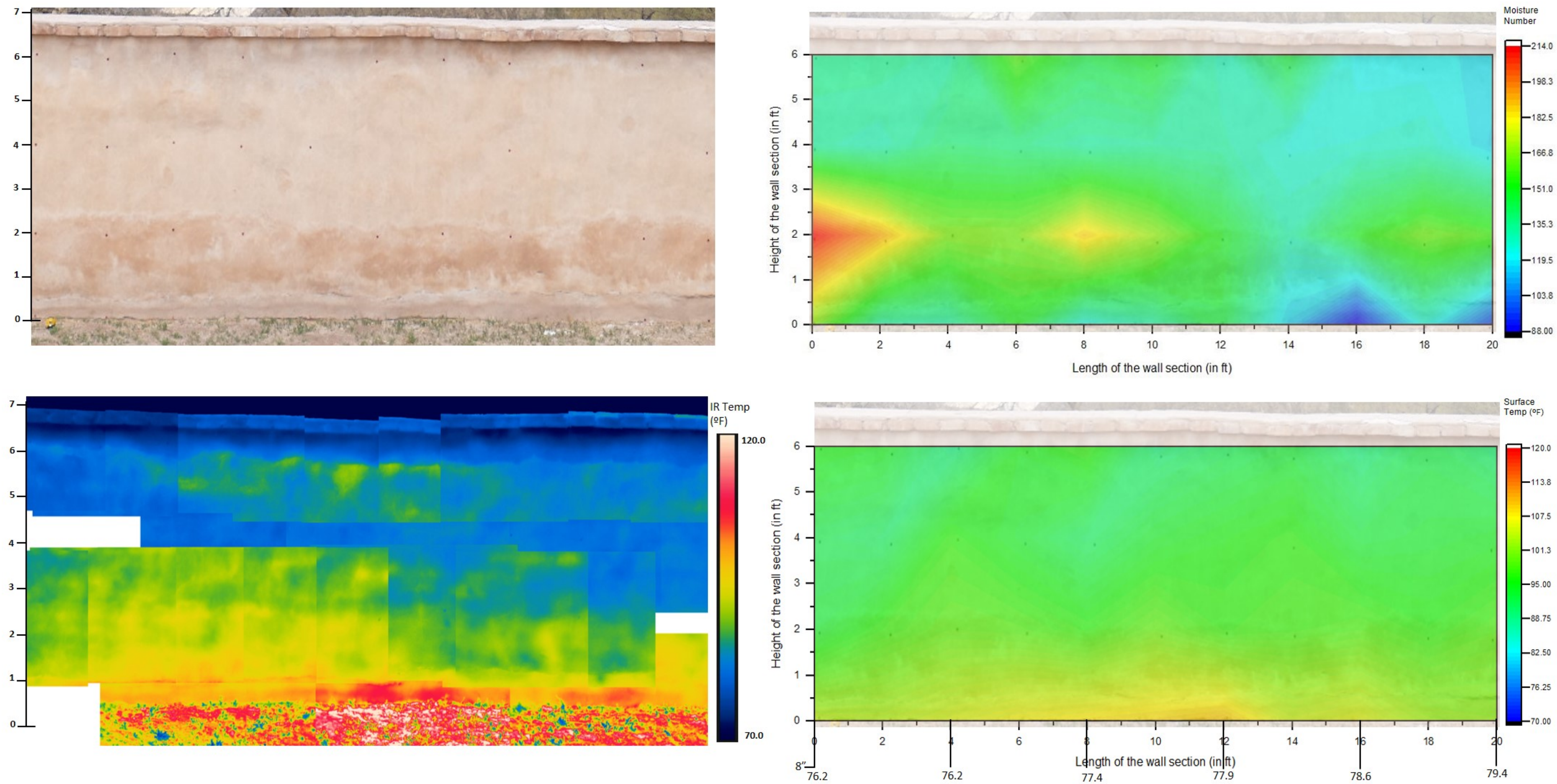


Figure F.9: (Clockwise starting from top left) Image of east-facing west wall section towards the south end, moisture meter readings contour plot, surface temperature readings contour plot and thermal image. The moisture and surface temperature contour plots (on the right side) have readings up to a height of six feet from ground whereas the left images have the entire wall section.

Conditions: This data set belongs to the east-facing west wall section towards the south end taken on 25th March 2021 from 9:47am to 10:51am. While taking the readings the air temperature varied from 65.9 ºF to 67.5 ºF, the relative humidity varied from 41.4% to 28.9% and the Dew point varied from 41.6 ºF to 34.7 ºF. There was overcast + windy the entire time. The surface temperature plot also shows the soil temperature (at a depth of 8 inch) in front of the wall, which has lower or similar temperature as the base of the wall.

Index