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Evaluation of Active and Passive Thermography for Rapid Detection and Characterization of Concrete Infrastructure Defects, Damage, and Deterioration

Research and Development Office
Science and Technology Program
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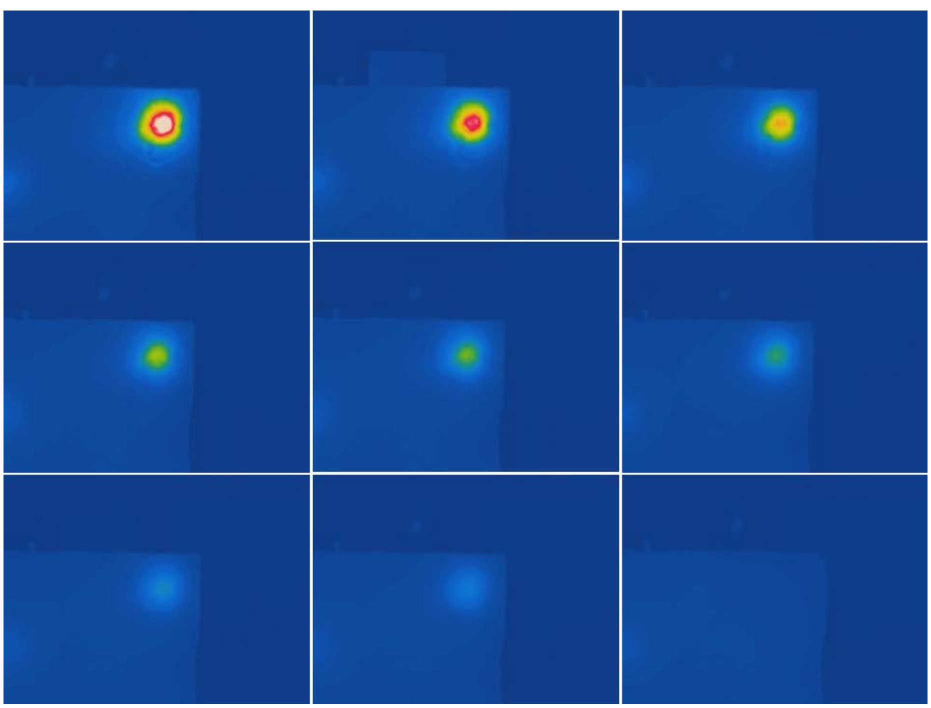

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Bureau of Reclamation
Research and Development Office

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14. ABSTRACT ***Reclamation has a multitude of aging concrete structures in various states of deterioration. The location, spatial extent and severity of concrete defects are usually poorly understood, and typical assessment methods are most commonly time and cost intensive with spatially limited coverage at oftentimes randomly selected locations. Thermal tomography (thermography) is one potential technology that could facilitate rapid identification and characterization of concrete defects/damage/deterioration in a significantly more efficient and spatially comprehensive fashion compared to conventional techniques currently being used. This scoping-level research project consisted of a literature and technology review to assess the current state of the art in thermography for civil infrastructure assessment, and several preliminary laboratory experiments were conducted. Results indicate that active thermography techniques hold significant promise in their ability to rapidly assess aging concrete infrastructure.***		
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Acronyms and Abbreviations

ASR	Alkali-Silica Reaction
ASTM	American Society for Testing and Materials
DOI	Depth Of Investigation
IR	Infrared
NDT	Non-Destructive Testing
NDE	Non-Destructive Evaluation
O&M	Operations and Maintenance
PPT	Pulsed Phase Thermography
PT	Pulsed Thermography
UAV	Unmanned Aerial Vehicle

Executive Summary

Problem

Reclamation has several large concrete dams and other large concrete infrastructural components considered to be "high-risk" due to their critical functions and locations relative to large downstream population centers (e.g., large economic losses and loss of life for downstream populations in the event of a catastrophic failure). Many of these structures are in various states of deterioration (e.g., experiencing wear and tear due to repetitive impact and motion damage or other cyclic phenomena such as freeze-thaw), increasing the probability of failures in certain plausible scenarios. The location, spatial extent and severity of concrete defects are usually poorly understood, and typical assessment methods are often conducted "blindly" (e.g., random placement of focused surveys and coreholes, without the use of additional information or prior knowledge of defect location/severity). As a result, there is the ever-present chance of underestimating the severity of damage to these structures and the subsequent overly liberal estimate of safety factors/risk.

New technologies are needed to facilitate rapid identification and characterization of concrete defects/damage/deterioration in a significantly more efficient and spatially comprehensive fashion than typical techniques currently used (e.g., spot-checking conditions via standard geophysical techniques or drilling/coring programs). Thermal tomography (thermography) is one potential technology that could achieve these goals and is the focus of this scoping-level research project.

Research Approach

This scoping-level research project consisted of a literature and technology review to assess the current state of the art in thermography techniques and their capabilities and applications for non-destructive testing and evaluation of concrete structures. This scoping-level effort also aimed to assess Reclamation's current capabilities for conducting thermography studies. Lastly, several preliminary laboratory experiments were conducted to evaluate thermal infrared camera hardware currently owned by Reclamation and to evaluate current resources, capabilities, and needs to support future research involving thermography.

Results and Recommended Next Steps

Results of this scoping-level research project indicate that active thermography techniques hold significant promise in the ability to help address many of Reclamation's technical challenges related to the assessment and maintenance of aging concrete infrastructure. Preliminary testing with existing Reclamation IR camera hardware and software indicate that future research efforts are immediately feasible using existing resources.

It is highly recommended that further conducting-level research efforts be funded and pursued to more closely evaluate and develop thermography capabilities at Reclamation.

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Problem Statement and Research Goals

Reclamation has several large concrete dams and other large concrete infrastructural components considered to be "high-risk" due to their critical functions and locations relative to large downstream population centers (e.g., large economic losses and loss of life for downstream populations in the event of a catastrophic failure). Damage and deterioration of concrete structures poses several safety and economic risks related to aging critical infrastructure and is oftentimes very difficult and costly to assess comprehensively using typical visual inspection and invasive techniques.

In the case of large concrete structures, distributed defects such as alkali-silica reaction (ASR) and cyclical freeze-thaw deterioration processes exacerbate maintenance challenges and the probability of certain failure modes. More localized issues can also increase the probability of certain structural failures, or simply lead to poorly performing structures, decreased water storage or conveyance capacity, and operations and maintenance (O&M) challenges and related costs. Some of these localized structural issues include poor bonding of adjacent concrete pours ("bad lift-lines"), concrete placement issues resulting in honey-combing and poor aggregate bonding, delaminations from underlying reinforcement, and the development of localized cracking due to interior stresses resulting from differential settlement processes, hydrostatic loading or differential curing, and thermal expansion/contraction processes.

New technologies are needed to facilitate rapid identification and characterization of concrete defects/damage/deterioration in a significantly more efficient and spatially comprehensive fashion than typical techniques currently used (e.g., spot-checking conditions via standard geophysical techniques or drilling/coring programs). Thermal tomography (thermography) is one potential technology that could achieve these goals and is the focus of this scoping-level research project.

The primary goals of this scoping level research project are to answer the following questions:

1. Can active heat-pulse or passive thermography be implemented in a manner that is technically and economically feasible for rapid and effective detection and imaging of concrete structure defects/damage/ deterioration in a field-scale implementation scenario?
2. What is a reasonable spatial resolution and reasonable depth of investigation (DOI) limitation for thermal tomography on concrete?
3. What are some of the main limiting factors in DOI and spatial resolution?
4. What are the economic advantages are possible from development and adoption of this technology compared to other more typical assessment techniques?
5. What are the current hardware and software resources available to Reclamation?
6. Is this research topic worth pursuing in subsequent conducting-level research efforts, and if so, what internal and external partnerships would facilitate subsequent research efforts?

Background

Thermography is a nondestructive, nonintrusive, and oftentimes a noncontact approach to mapping of thermal patterns or "thermograms" on the surface of objects. Thermography is one category of remote sensing non-destructive testing (NDT) technology that has been researched and developed for several years, with most recent advancements involving hardware and subsequent modeling techniques to attempt better imaging of subsurface defects. There is even a dedicated peer-reviewed scientific journal dedicated to the topic, titled *Quantitative InfraRed Thermography* that was founded in 2004 and is currently in its 16th volume.

In its most basic form, thermography involves thermal imaging of a target object or surface using of an infrared (IR) thermal imaging camera to record spatiotemporal contrasts (e.g., anomalies) in surface temperature associated with changes in thermal properties of subsurface materials. These spatial changes in thermal properties are most often associated with a change in subsurface material types, the presence of subsurface voids, or due to damage (e.g., lower density materials).

Due to the rather simple approach to data collection, thermographic NDT techniques potentially offer a means to interrogate entire surfaces of large concrete structures (located within line-of-site of an infrared thermal camera) for shallow damage and deterioration patterns in a spatially comprehensive fashion over a timeframe of 24 to 48 hours or less. Specifically, both active and transient (e.g., applied heat pulse and transient heat source) thermography techniques are promising candidates for rapid detection and mapping of structural conditions and shallow defects within large concrete structures.

Active and Passive Thermography Overview

Passive

Passive thermography generally involves the use of IR cameras for imaging or monitoring of scenes or objects for anomalous thermal signatures of concern. Here, features of interest exhibit a higher or lower [steady-state] temperature than the background, with many applications ranging from electronic and mechanical device health monitoring to surveillance of people exhibiting abnormally warm skin temperatures (e.g., related to illness, nervousness, lying, and security breach concerns). This approach to thermography holds some promise in mapping different material types or material properties based on spatial variations in steady-state temperatures during static thermal loading conditions. For example, spatial variations in material density and related thermally conductivity within objects may result in spatial variations in surface temperature if boundary conditions are appropriate (e.g., the back side of the test object is in contact with a relatively warm or relatively cool substrate).

Active

Conversely, active heat-pulsed thermography (PT) techniques generally involve the application of a pulse of heat (or a cold pulse, relative to background steady-state temperatures) to a test surface or target object and then subsequently monitoring the temperature across the surface of the target during the heating and/or during the cooling phase of the experiment. Additionally, either reflection or transmission thermography can be implemented to detect subsurface anomalies. The reflection approach involves use of the heat source and IR sensor on the same side of the target, while transmission thermography involves heating one side of a target and monitoring the opposite side of the target with IR sensors. Here, transmission thermography requires physical access to both sides of the target, which may or may not be impractical in many applications.

A focused heat pulse can either be applied directly to the target through physical contact (e.g., heat plate) or with the use of high-power lasers, or it can be applied to broader area of the target surface with the use of a nearby thermal radiation source such as arrays of high-wattage (1000W or more) heat lamps or induction coils. An example of an active thermography experiment taken from (Khan, Bolhassani, Kontsos, Hamid, & Bartoli, 2015) is depicted in Figure 1. Here, a small array of heat lamps are used as an active heat source, with the target consisting of masonry walls with engineered defects (poor grout bonding).

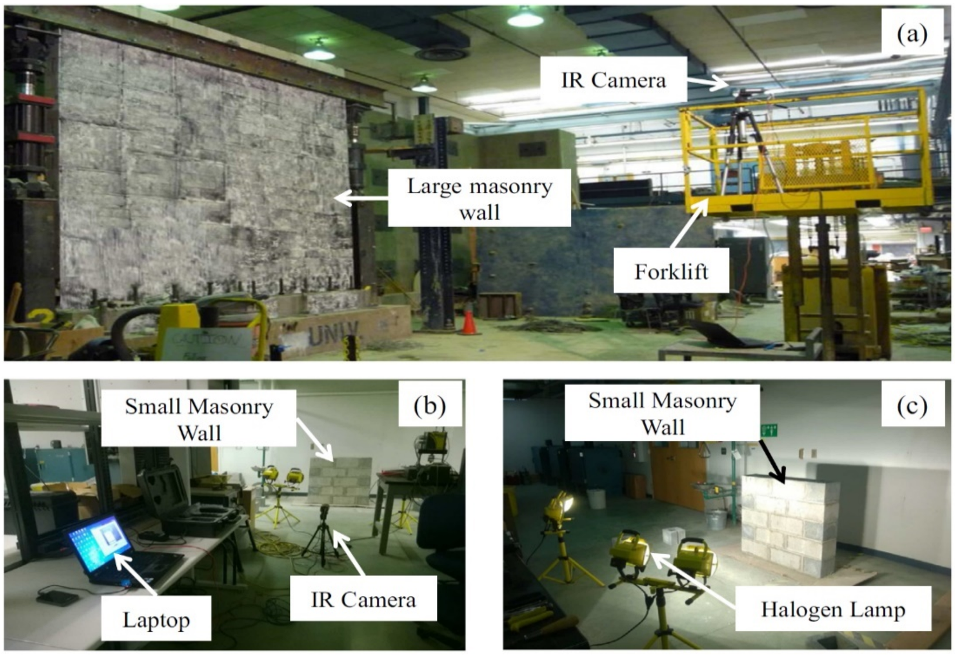

Figure 1. Example of active thermography experimental setup using halogen lamps for a heat source (Khan, Bolhassani, Kontsos, Hamid, & Bartoli, 2015).

Another example of active thermography applied to concrete defect detection is presented in Figure 2, where a concrete target was engineered with defects of various dimensions and depths placed behind the test surface (only up to 3cm depth below surface). General takeaways from this study include:

1. Smaller and deeper defects are proportionally difficult to detect.
2. Longer heating helps to reveal smaller and deeper defects.
3. Longer cooling times help to reveal smaller and deeper defects.
4. The peak thermal contrast of an anomaly (relative to background steady-state temperature) is proportional to the depth to defect.
5. IR thermal technique can be effectively used to determine the size and depth of delaminations at the surface of concrete structures.

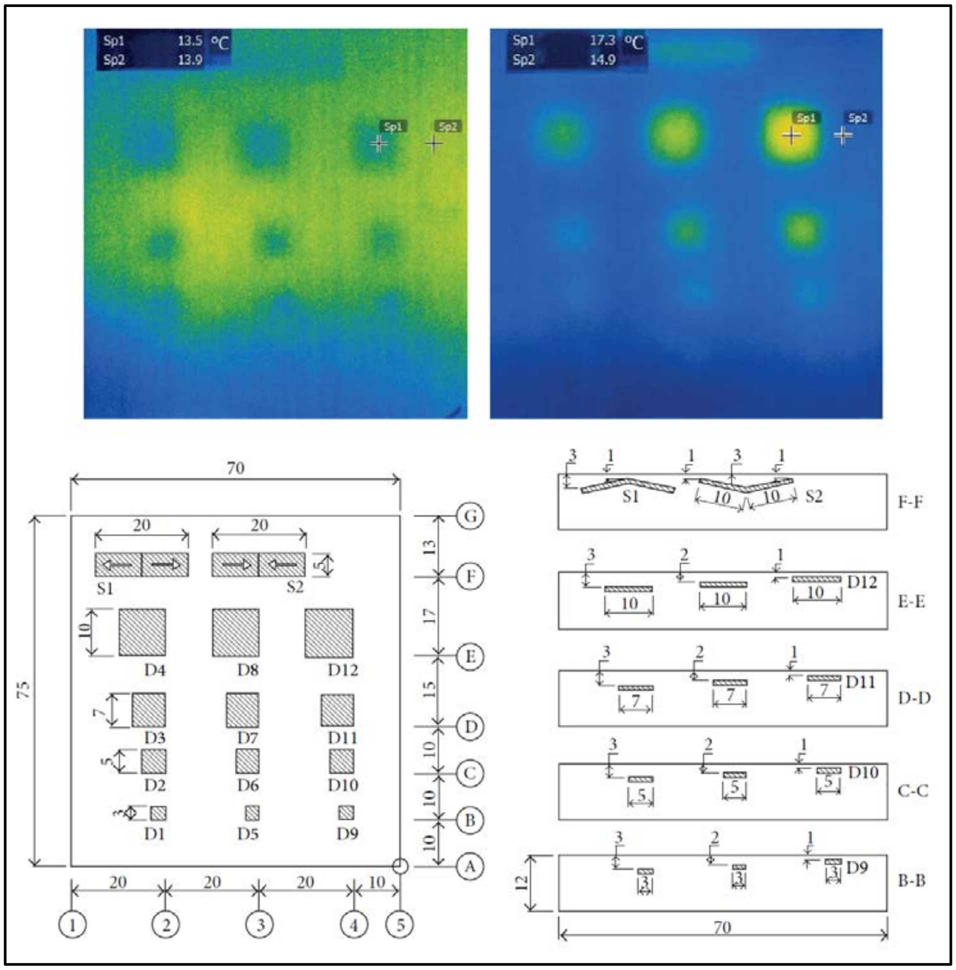

Figure 2. Example of active thermography experimental results using halogen lamps for a heat source, with engineered delaminations at various depths and dimensions (Jungwon, et al., 2016).

As depicted in the above examples, active PT requires physical access to within some proximity of the surface area to be tested/interrogated for application of heat (or cold) to the test surface. As a result, this approach has several practical limitations in terms of the logistics required for use on large structures (e.g., ropes team access, etc.). One of the main benefits of an active approach is the added experimental control obtained by using an active heat source. For example, the magnitude and duration of heat application can be carefully controlled to optimize results. Therefore, active thermography techniques could be better suited for smaller target surfaces or objects that have easy physical access or in scenarios where the target surface doesn’t receive adequate passive heat sources (e.g., inadequate sunlight exposures). An example of a commercially available PT system is depicted in Figure 3 (Thermal Wave Imaging, 2019).

Figure 3. Example of commercially available active pulse thermography imaging system (Thermal Wave Imaging, 2019).

In contrast, there is the possibility of using lower frequency ambient changes in thermal loading of a test object (e.g., changes in solar radiation applied to an object throughout a given day) in order to achieve the same goals as active source PT. Therefore, no proximal physical access to a target surface is necessary, as an ambient thermal excitation process would be monitored via remote sensing by a thermal camera located at a greater distance from the surface of interest. This ambient approach could theoretically be conducted from up to several hundreds of feet away from the surface of interest. Here, the practical limitations and primary considerations include the requirement for sufficient sunlight exposure, direct line-of-sight between the thermal camera and the test surface, and a drop-off in spatial (per-pixel) resolution of the thermal imagery as a function of distance from the surface of interest.

A variation to the general PT approach that utilizes ambient heat sources has been implemented on larger field scales for the sake of mapping bridge deck delaminations. This approach to active thermography holds great promise for adoption by Reclamation and other stakeholders for assessment of large concrete structures (e.g., dams). This technique has been developed into an American Society for Testing and Materials (ASTM) standard ASTM D4788 (ASTM, 2003). In this ASTM standard, a vehicle-mounted scanner is driven along bridge decks to map temperature distributions across the deck surface. The major takeaways from this specific application include the following:

1. Delaminations act as thermal insulators for conductive heat flux within the test object, resulting in these damaged zones being warmer during the day-time (heating phase) and appear as cooler spots relative to background temperatures during the night (cooling phase).
2. Delaminations of typical depth require approximately three hours of passive heating from direct sunlight in order to achieve a 0.5-degree Celsius temperature contrast with surrounding bonded areas.
3. Both a longer and stronger heating phase, as well as longer cooling phases, help to illuminate deeper defects.

4. Data quality is hindered by surface debris and wind exceeding ~30 miles per hour between the IR camera and test surface.
5. The thermal contrast of delaminations will decrease during the winter months, mainly due to the decrease solar wattage and resulting passive thermal flux into the test surface.
6. Temperatures below 0-degrees Celsius can result in false negatives due to infilling of ice in delaminations.
7. The surface should generally be clean and dry for detection of subsurface defects.

Lock-in Thermography

In addition to analyzing active PT data in the time-domain, these data can be transformed to the frequency domain via a Fourier Transform, allowing for analysis of the phase spectra of recorded thermal images. This frequency-domain approach to analyzing PT data is referred to as pulsed phase thermography (PPT). Previous work in this approach to PT data analysis has shown that greater depths of investigation can be achieved with the use of PPT (Ishikawa, Hatta, Habuka, Fukui, & Utsunomiya, 2012). Lock-in Thermography is a specific term used for PPT analysis techniques that utilize time-varying heat sources, such as sunlight described above.

The basic idea of lock-in thermography is that the temperature modulation applied to a test surface propagates into the test object as a "thermal wave". As this wavefield experiences reflections at boundaries like all other waves, the temperature modulation at the surface is considered to be modified by thermal waves reflecting back from the inside test object.

Here, the contribution of the reflected signal can be separated out by means of calculating the phase angle between the applied thermal loading function (e.g., cyclical heating by sunlight) and local thermal responses recorded across the target surface. The following quote is taken from Ishikawa, Hatta, Habuka, Fukui, & Utsunomiya, (2012):

> *"If the temperature field is monitored during the modulated illumination with a thermography camera, Fourier analysis performed at each pixel provides magnitude and phase of the local response. These two quantities can be used to present the relevant information as another kind of image. The magnitude image is affected by inhomogenities of optical surface absorption, infrared emission and distribution of optical illumination. However, in the phase image each of these effects is eliminated when the evaluation is performed at each pixel. This is of relevance for aerospace structures with typical sizes that make homogeneous optical illumination difficult."*

This specific analysis approach offers promise to successful application of PPT on large concrete structures, as it helps to automatically correct for changes in surface roughness, thermal emissivity variations, and the challenges related to thermally stimulating an entire large surface evenly.

Previous Work and Existing Resources

Industry and Academia

As mentioned above, extensive industry-based and academic-based research and development of thermal-imaging devices, NDT, and non-destructive evaluation (NDE) techniques, including various approaches to active pulse and passive thermography, has already been conducted. There are several peer reviewed journals that revolve around thermal physics and its applications within the NDT industry, many with a focus on micro-scale assessments of material properties and health condition monitoring within the aerospace and automotive industries.

The analysis of heating-up and cooling-down processes with an internal or external heat source (i.e. radiator) is a well-established technique for the characterization of non-metallic materials (XPV, 1993; Danesi, Salerno, Wu, & Busse, 1998). Up to now, there are only a few examples where active thermography has been applied successfully in civil engineering (Maierhofer, et al., 2006). The method is very useful for the determination of the built-in position of anchoring elements at curtain facades and for monitoring of reinforcing steel in concrete structures as well (Weise, et al., 1995; Bjegovic, Mikulic, & Sekulic, 2001).

While over 40 publications on the general topic of active PT, PPT, and passive thermography were obtained and reviewed, an extensive presentation of the literature review is beyond the scope of this report. However, it should be stated that several notable publications related to the use of active PT for civil engineering and NDT applications were identified (Vavilov, Kauppinen, & Grinzato, 1997; Maierhofer, Brink, Rollig, & Wiggenhauser, 2002; Manning & Holt, 1980; Love, 1986; Noszczyk & Nowak, 2019;). Similarly, several notable publications related to the use of PPT and lock-in thermography for NDT applications were identified (Sun, 2016; Weritz, Arndt, Rollig, Maierhofer, & Wiggenhauser, 2005; Ibarra-Castanedo & Maldague, 2005).

Reclamation

To date, Reclamation has not performed formal research related to active or passive thermography for NDT applications. However, Mathew Klein of Reclamation Technical Service Center’s Materials Engineering and Research Lab Group has conducted one informal experiment with the use of an unmanned aerial vehicle (UAV) thermal camera, collecting thermal images during the day and at night. Like the ASTM bridge deck inspection technique described above, this effort was to simply see if delaminations could be visually identified as hot or cold spots relative to intact background temperatures at each respective recording time. This effort involved the use of a UAV mounted FLIR Vue Pro R 640 thermal imaging camera. No further analysis was performed with these data.

Reclamation TSC scientists have recently been working with various thermal cameras (including the UAV-mounted thermal camera mentioned above), and these may be made available for future experimentation. One issue with the FLIR Vue Pro camera is the listed specifications for accuracy (+/- 5 degrees Celsius), where the desired accuracy for most thermography applications is +/-0.5 degrees Celsius. While the reported accuracy of this specific IR camera is about one order of magnitude less than optimal, future research would be required to verify if the precision is sufficient for thermographic applications.

Nathan Myers of Reclamation Technical Service Center's Hydropower Diagnostics and SCADA Group has a Flir E95 hand-held/tripod-mounted thermal IR camera with reported accuracies of up to 2-0.5 degrees Celsius, and a range of built-in features including high frame-rate video capture, time-stamped timelapse image capture, and calibrated numerical outputs.

Preliminary Laboratory Experimentation

As part of this scoping-level research project, some preliminary laboratory experiments were carried out in the Hydraulic Laboratory located in Building 56 on the Denver Federal Center. For these experiments, three different concrete targets were used for active and transient PT experiments. The main objectives of these tests included the following:

1. Evaluate basic functionality and usability of the Flir E95 camera hardware and data post-processing freeware currently available to Reclamation.
2. Collect several active (heat gun) and ambient (sunlight heated) PT datasets on various concrete targets.
3. Initial development of custom image processing and data analysis codes to handle the Flir E95 output data files (.JPG images and exported ASCII data matrices).

Several initial thermography experiments were performed using existing concrete casts made available for testing. Specifically, the concrete cube and two concrete beams depicted in the left and right photos of Figure 4, respectively, were used as thermography targets. The concrete block is approximately 1 meter on each side, and the concrete beams had approximate dimensions of 2 meters by 35 centimeters by 20 centimeters. For this preliminary testing effort, the concrete block was used for active PT testing, and the two concrete beams were used as targets for ambient PT tests.

The two beams were originally used for point-load strength testing, and while little is known about the difference in composition of these two beams, it is assumed that they were poured with two different concrete mixes (e.g., different water content, aggregate percentage or type or size), and may have different curing histories (e.g., controlled humidity and/or temperature during curing). These two target concrete beams were allowed to heat up in direct sunlight for several hours (from sunrise until about noon). Subsequently, the two beams were quickly moved into the Hydraulics lab with a forklift and timelapse thermography was initiated within approximately one minute. The beams were allowed to cool off for several hours during timelapse photographic monitoring.

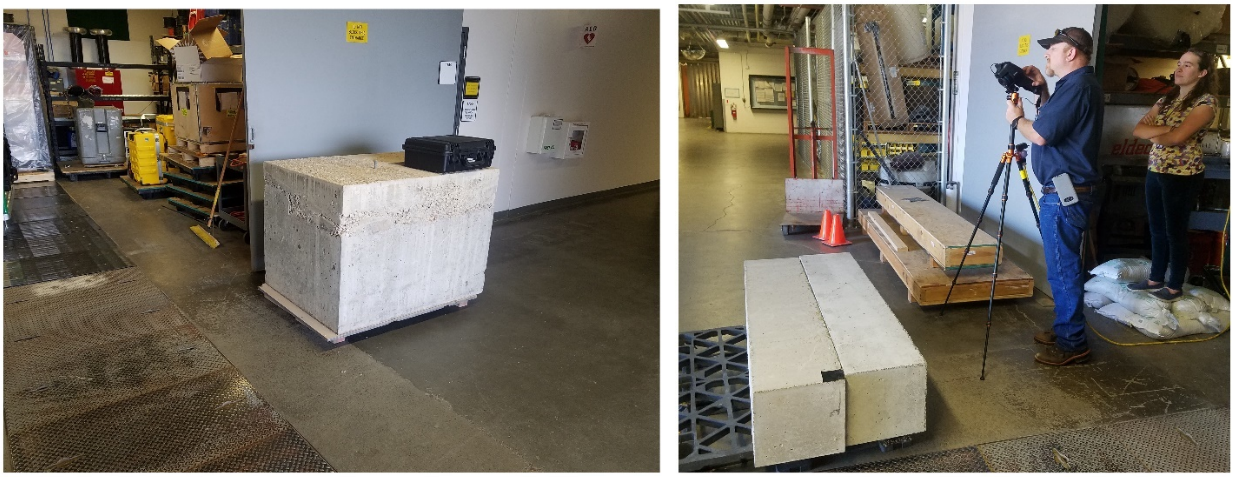

Figure 4. Concrete targets used during preliminary testing of active pulsed thermography (block in left photo) and for ambient pulse thermography tests (two beams in right photo).

The concrete block was cast several years ago and was specifically designed to contain several engineered defects including simulated voids (plastic bags with bare aggregate), poorly bonded lifts, and poorly mixed lifts (inadequate cement mix or intentionally entrained air pockets). Several points labeled A through F in Figure 5 were selected for active heat pulse thermography testing. The locations were chosen to target visually apparent shallow/surficial defects and variations in concrete quality. Additionally, a rough surface was scratched onto the top of the test block, and so points D and E were placed on opposing sides of a corner to test the effects of surface roughness on thermal emissivity (the ease of thermal reradiation from a material). For each test point, a 500W electric heat gun was used to apply a thermal heat pulse for 20 seconds from an approximate standoff distance of 2 inches from the concrete surface. For the six test points, initial surface temperatures ranging from approximately 80- to 130-degrees Celcius (180-260 degrees Fahrenheit) were achieved.

Figure 5. Photos showing test points A through F targeted during active heat pulsed thermography experiments. The locations were selected to attempt targeting both good and poor-quality concrete within the shallow subsurface of the test block. Points D and E were selected on opposing sides of a corner in order to test the effects of surface roughness in active pulse tests.

Preliminary Testing Results

Ambient Pulse Thermography

Several thousand thermograms were obtained during three different ambient heating/cooling PT tests. Figure 6 presents two example thermograms taken from one of these experiments, showing the two concrete beams at the start of recording time (T=0) and five hours after cooling (both beams are visible in each photo). The difference in temperature contrasts between the two beams at early and late times depicts an apparent difference in concrete and/or aggregate properties and resulting thermal properties and cooling rates. Specifically, both beams had similar surface roughness and concrete color (likely the same emissivity), and yet the beam on the left side of each photo had a higher initial temperature and then cooled off noticeably faster. This observation suggests that the left-hand beam has a lower thermal inertia likely arising from a lower mass density and thermal conductivity. The main takeaway here is that a significant heating of concrete can be achieved simply with ambient sunlight exposure, and that the resulting timelapse patterns and trends observed in thermograms can successfully image spatial changes in material properties of interest. This offers promise in applying the technique to large concrete structures.

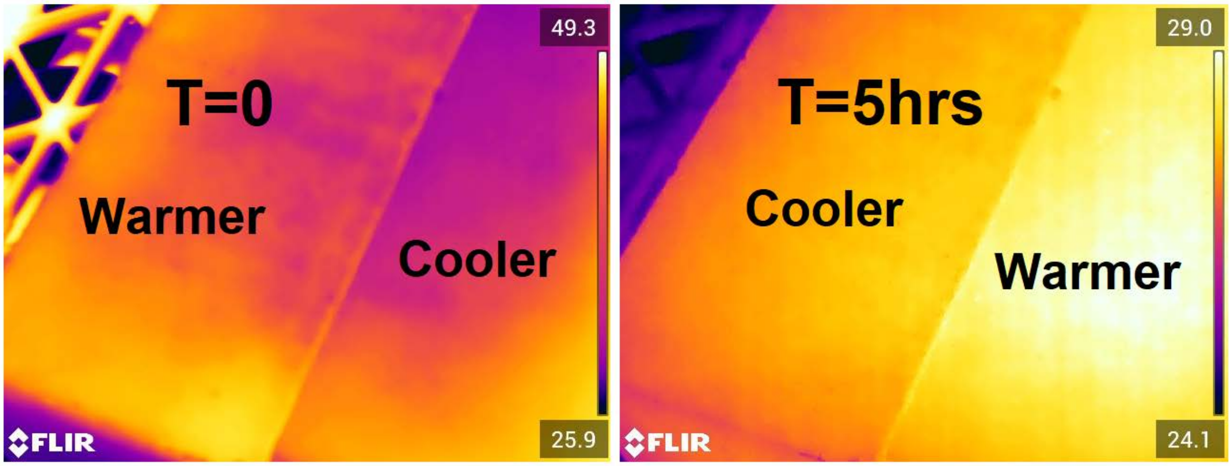

Figure 6. Two thermograms showing the two concrete beams at the start of recording (T=0) and five hours after cooling. Ambient heating of the beams was achieved by sunlight exposure from sunrise to approximately noon. The difference in temperature contrasts between the two beams at early and late times depicts a difference in concrete and/or aggregate properties.

Active Pulse Thermography

Figure 7 shows a screen capture of the free Flir image processing software FlirTools® with several thermograms loaded from one of the six active PT experiments conducted on the concrete block. The mosaic shows the heat pulse as a yellow and red bullseye pattern that is observed to cool off over time (each frame is approximately 4 seconds apart). The software allows for manual exporting of individual thermal images to ASCII .CSV files for post-processing. An example of exported thermogram data for test Point A are plotted as a color contour surface plot in Figure 8. The shape of the peak has a nearly perfect Gaussian distribution, suggesting a uniform radial thermal conductivity (no significant lateral anisotropy in thermal properties). It is hypothesized that the presence of a thin crack in the concrete would result in an asymmetric heat distribution and could be detected using simple analysis of the active PT image. These data are in the form of a matrix containing temperature values recorded at each pixel. Therefore, post processing of data can be performed on a pixel-by-pixel basis.

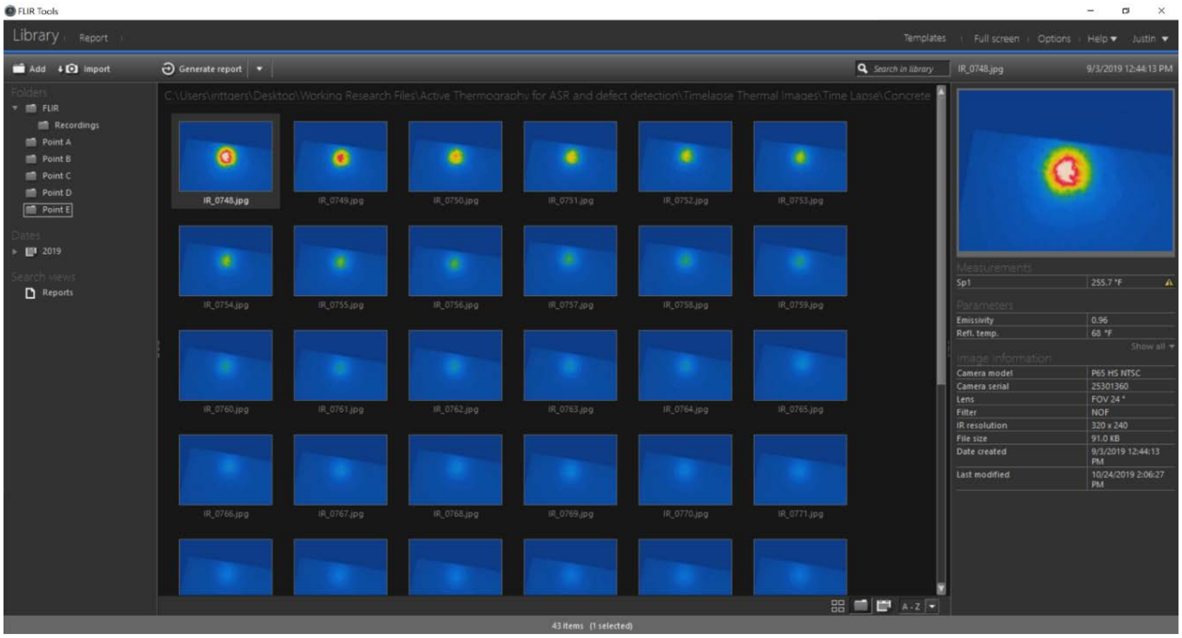

Figure 7. Screen capture of free Flir image processing software FlirTools®. The software allows for manual exporting of individual thermal images to ASCII .CSV files for post-processing.

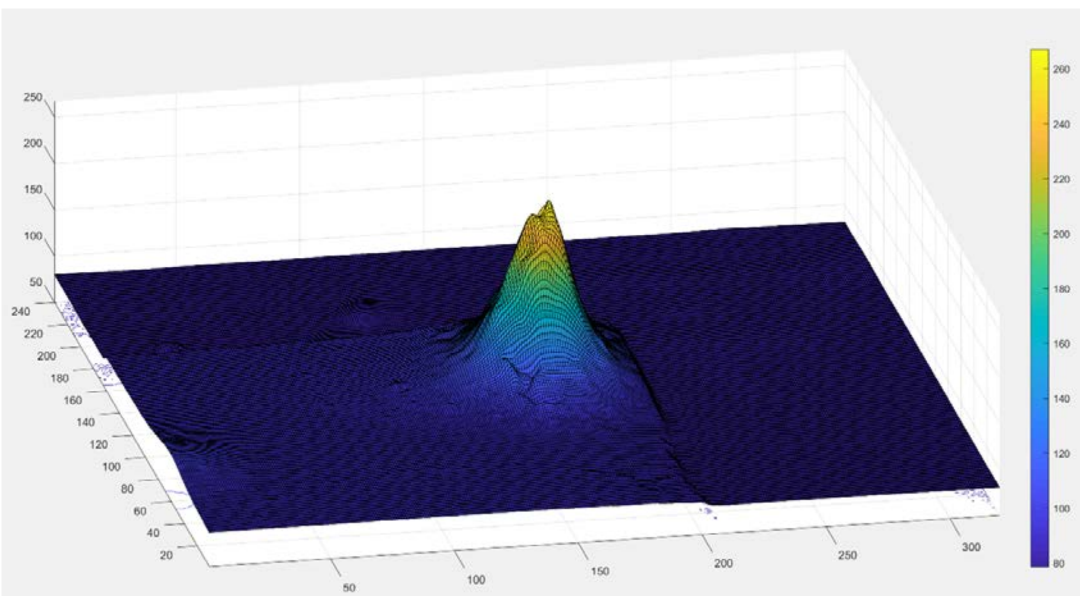

Figure 8. Example of exported thermal data for an early timeframe during active heat pulse testing at "Point A" of the concrete target block. The central spike shows the location of the heat pulse, with initial temperature of approximately 130-degrees Celsius (265-degrees Fahrenheit). The corner and edges of the block can be seen in the data relative to cold background values.

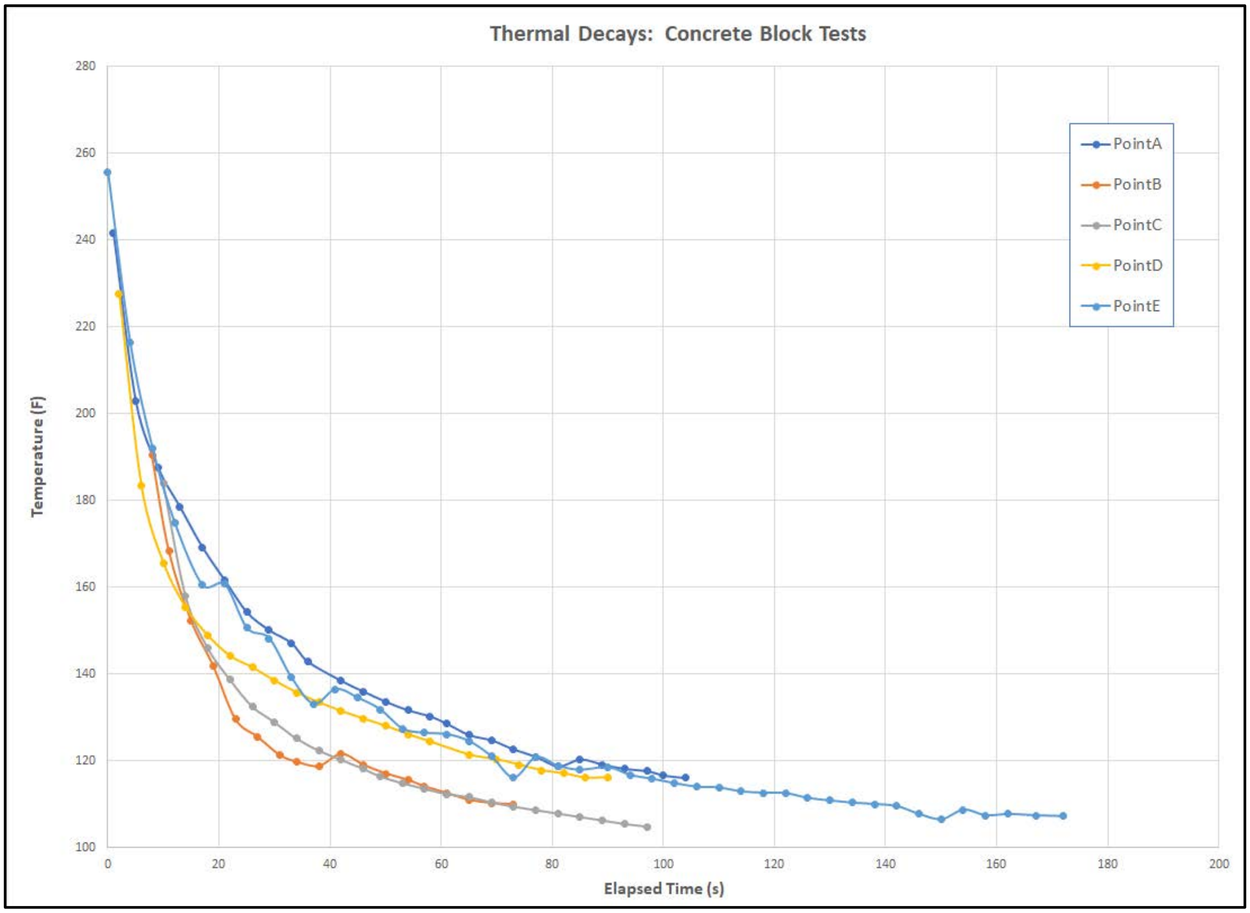

Figure 9. Five time series thermal decay curves for test points A through E on the concrete block target. Initial temperatures have been aligned to a single curve to demonstrate the different decay rates associated with the different locations on the target block. During cooling, a heat pulse will generally cool faster in areas of damaged or lower density (lower thermal conductivity) concrete, as is seen with Point B (lower orange curve) relative to Point A (upper blue curve). Noise on each curve is due to hand-shaking while collecting data.

The E95 IR camera and software also provide a test point temperature reading at a centralized crosshair. During each of the six active PT experiments, the camera was aimed such that the crosshair was centered on the heat pulse, providing the approximate peak temperature at the center of each heat pulse versus time. These data were extracted and used to produce the thermal decay curves plotted in Figure 9 for test points A through E on the concrete block target (data for test Point F were not saved for some reason). Initial temperatures have been aligned to a single curve to demonstrate the different decay rates associated with the different locations on the target block. During cooling, a heat pulse will generally cool faster in areas of damaged or lower density (lower thermal conductivity) concrete, as is seen with Point B (lower orange curve) relative to Point A (upper blue curve). Noise on each curve is due to hand-shaking while collecting data.

Future work

The photo depicted in Figure 10 shows the two concrete beams after disection and coring. Smaller cubes and cores were taken fom each of the two beams to enable closer inspection of interior concrete characteristics and to enable measurement of mass density of each beam. Samples have been saved for future testing of density and other material properties (e.g., thermal conductivity can be measured directly with a small lab device currently owned by Relamation. These tests are planned for the samples taken from the two beams, for samples that will eventually be extracted from the concrete cube, and any additional targets used in future continuation of this initial scoping-level research.

Figure 10. Photo of test beams used in ambient pulse thermography tests after dissecting and coring of the beams for enabling density measurements of smaller portions of the beams.

Future work should include more rigorous data collection and analysis of thermal properties and how they relate to other properties of interest, such as density. There may be the opportunity to develop structure-specific correlational relationships between thermal properties and other material properties of interest, such as shear strength or mass density. Code development will be required to perform quantitative analysis of entire images, and additional Flir Software will be required to enable batch pre-processing and exporting of thermograms to ASCII data files for post processing and modeling. Specifically, developing semi-automated capabilities for performing lock-in PPT analysis will be a priority, enabling unbiased interpretations of entire images on a pixel-by-pixel basis. This will be the first step towards enabling rapid characterization of concrete integrity across entire large structures.

Challenges and Limitations

One of the main limitations of PT is a lack of DOI, typically limited to 10-15cm in previous studies. While this relatively shallow DOI limits thermography's direct applications to near-surface assessments, much of concrete deterioration occurs within this shallow depth range. Furthermore, shallow indicators of deterioration are oftentimes present in the same locations as deeper underlying issues that may exist beyond the DOI of thermography.

Another major limitation (or challenge) involves the logistics for application to large structures, which involves the challenge of heat application when using active PT approaches. Active PT will still require physical access to the target surface, resulting in added time and cost for data collection. This may not always be feasible from a logistical or safety standpoint, therefore there is a need for further assessment and development of ambient PT techniques that utilize ambient thermal heating by means of either diurnal ambient temperature fluctuations or by direct sunlight exposure. Direct sunlight exposure has already been shown here and in previous work to be sufficient, but it remains to be seen if air temperature fluctuations (e.g., differences between day and nighttime temperatures) will provide a sufficient thermal pulse for the sake of PT imaging. If not, ambient PT techniques will most likely be limited to large structures that have adequate daylight exposure (e.g., south facing arched concrete dams or spillway walls).

Lastly, thermogram spatial resolutions will decrease with increasing distance form the target surface. Therefore, the ability to either collect data using UAV-mounted IR cameras, or by other means of generating mosaics of closeup thermograms, will need to be considered for future application to large structures.

Benefits and Costs

It should be noted that the following costs comparison is only relevant to shallow DOIs, as discussed in the Challenges and Limitations section above. It is not intended to suggest that thermography can directly replace these other techniques. The cost comparison is simply to demonstrate the potential for thermographic techniques to provide spatially comprehensive maps of shallow damaged or deteriorated concrete in a rapid and affordable manner. The primary benefit is a means to help guide and focus subsequent more detailed yet costly techniques such as coring or geophysical surveying that provide unique information with greater depths of investigation compared to thermography. Lastly, while thermographic techniques do not directly provide the same material properties as these other techniques (e.g., does not provide seismic velocity), it could be combined with other techniques to help interpolate, extrapolate, or otherwise predict other material properties of interest through the careful development of site or structure-specific correlational relationships. Ultimately, this would help to maximize the value of information obtained with these more focused investigations.

As an example of the potential cost savings related to the use of thermography for the sake of mapping areas experiencing accelerated concrete deterioration or damage (e.g., from freeze-thaw, ASR, or shallow delaminations) compared to other techniques, we can draw from a recently completed Dam Safety Program-funded research project conducted by Dan Liechty of Reclamation Technical Service Center's Engineering Geology and Geophysics Group (Liechty & Rittgers, 2019).

Here, various geophysical imaging techniques were evaluated for their ability to detect and map ASR deterioration that has been a known issue at Seminoe Dam for several years. The main component of this research project involved the use of Reclamation's Ropes Access Team for obtaining physical access to the face of Seminoe Dam in order to enable data collection (Figure 11). While several geophysical imaging techniques were deemed successful for imaging ASR deteriorations, the resulting data coverage was very limited (data only collected along two sections of the dam, as depicted in Figure 12), the data were extremely time-consuming to collect (ropes preparations and data collection activities took a multi-person crew several days to complete), and the costs associated with data collection were approximately $55,000. Data processing and modeling brought the project budget to just slightly less than $100,000, so a single surveying technique could be deemed to cost one third of this overall project budget (~$35,000). This is a reasonable cost estimate for a ropes access-based geophysical survey with similar limited data coverage (data collected along one or two adjacent vertical survey transects. Since two transects of each data type were collected, we could estimate the total cost per transect as $17,500.

In contrast, ambient pulse thermography could hypothetically be collected by a single person using a tripod-mounted IR camera within 24 to 48 hours, providing comprehensive data coverage of the entire downstream face of a concrete dam, and data analysis could be partially or fully automated, providing results in a matter of hours. Once capabilities are fully developed, this approach would cost less than $15,000 to complete at most structures (including travel and labor/non-labor costs related to data collection and reporting). A simple comparison of costs suggests that thermography would cost only ~50% of the more expensive approach to a very basic and spatially limited ropes-team geophysical survey.

Furthermore, if one of these more traditional approaches (e.g., geophysical surveying techniques) were implemented in order to achieve a similar data coverage provided by thermography, the resulting costs would scale accordingly. Using the Seminoe Dam with approximate dimensions of 400 feet wide by 200 feet tall as an example, a Flir E95 camera with 464 x 348 pixel resolution could be positioned to provide 464 vertical rows of data coverage that extend the full height of the dam. To achieve this data coverage density using a geophysical surveying technique would hypothetically require the same number of vertical ropes-access surveys to be conducted. This would result in an approximate total cost of $17,500 X 464=$8,120,000. Using this estimated value, a cost savings factor of 541X would be achieved with the use of thermography.

Finally, to modify the basic cost comparison above to be more realistic, a ropes-access geophysical survey would be implemented in a manner to obtain a reasonable data density (meaningful to the technique being used) and not to exactly match the resolution of thermographic imaging. Specifically, geophysical surveying would likely be implemented to achieve the same spatial coverage as the thermographic imaging approach, but not with the same spatial resolution (1 foot transect spacing would be overkill and would not provide unique information from adjacent transects). Here, a vertical transect spacing of no less than 10 feet would be used, and the cost saving factor would be adjusted accordingly. Considering this modification to the above cost comparison, a 10 foot transect spacing would result in an approximate total cost of \$17,500 X 46=\$805,000. Using this estimated value, a cost savings factor of 54X would be achieved with the use of thermography.

While the above cost comparison is only hypothetical, it points to the inherent value of first implementing a more rapid and spatially comprehensive screening approach like thermography in order to better guide subsequent more expensive techniques (e.g., geophysical imaging surveys). Thermography cannot replace these other more expensive imaging techniques, but it could be used to help identify the need for these other approaches and help guide placement of other data collection efforts (including core placement for sample extraction).

Figure 11. Photos showing ropes access supported geophysical data collection along a vertical seismic survey transect mounted down the face of Seminoe Dam in Wyoming. These data were collected as part of a research project related to ASR detection with the use of various geophysical techniques.

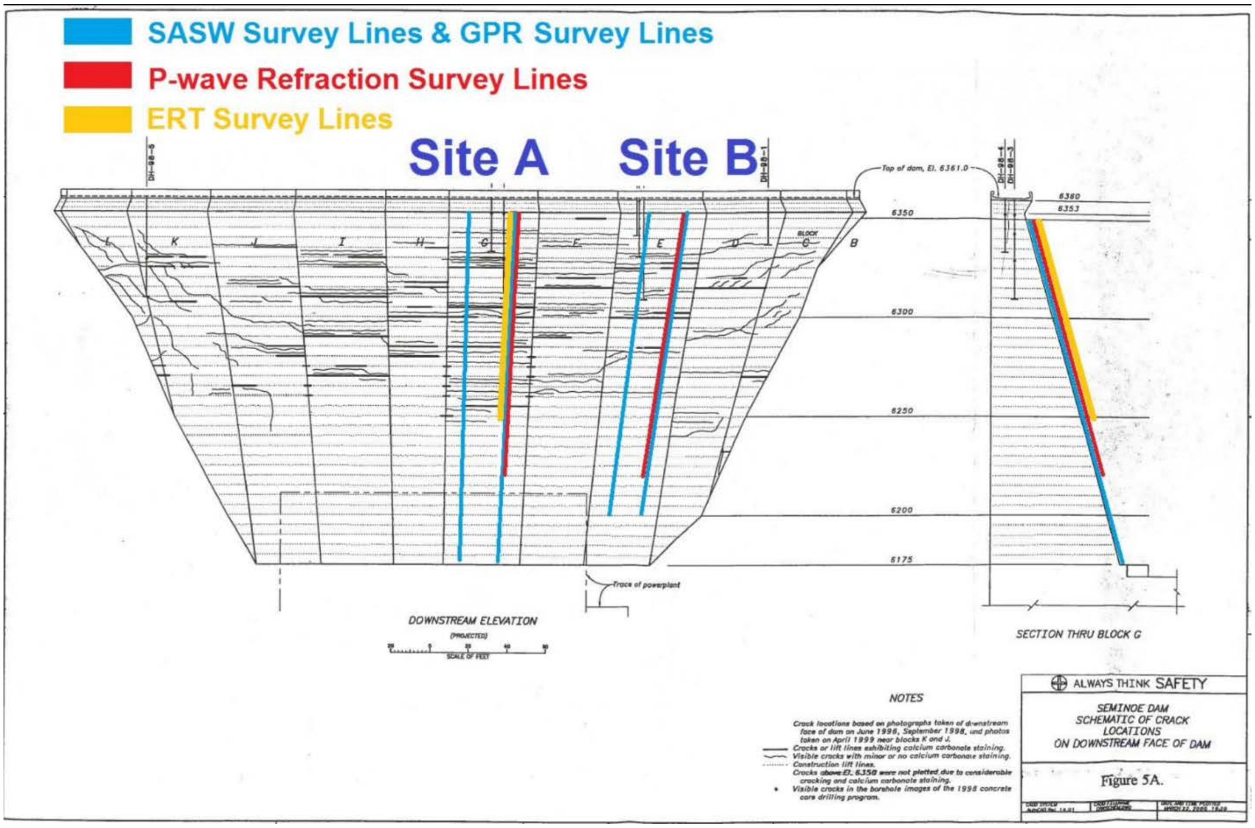

Figure 12. Schematic of the downstream face of Seminoe Dam (left) and cross-sectional side-view (right) depicting the locations of various geophysical surveys conducted as part of a Dam Safety Program Technology Development research project. These three data types with fairly minimal data coverages cost approximately $55,000 to collect, required physical access along the length of each transect, took several days to collect, and took several weeks to process the resulting data (Liechty & Rittgers, 2019).

Conclusions

Based upon the literature and technology review performed as a part of this scoping-level research, and based on the results of preliminary lab testing activities, it is apparent that thermography could be applied to rapidly identify locations of concrete defects/damage/deterioration in a far more efficient and spatially comprehensive fashion compared to typical techniques currently used (e.g. spot-checking conditions via standard geophysical techniques or drilling/coring programs). Thermography offers a possible means to interrogate entire surfaces of large structures (located within line-of-site of the thermal camera) in a comprehensive fashion within 24 to 48 hours using only an IR camera. This would by far surpass current data production rates, benefit/cost ratios, and increase spatial coverage and resolutions of current data collection techniques.

In addition to lab-based testing and development of analysis techniques, subsequent research efforts could immediately incorporate data collection at large structures, adding value to the results obtained. Due to the relatively simple nature of the data collection approaches of passive thermography, minimal training would be required for data collection, enabling area offices and other non- TSC entities to collect data required for subsequent analyses. While some preliminary data processing code has been developed, further work will be needed on this component.

At a minimum, this technology could provide a means to rapidly categorize and prioritize large numbers of structures/components within Reclamation’s inventory for subsequent inspection and/or repair efforts. Furthermore, this technology could be extended to long-term (repeated) monitoring and change-detection at a given structure.

Recommendations for Next Steps

The primary recommendation stemming from this scoping level effort is to support continuation of thermography research by funding subsequent conducting-level research activities.

Specific recommendations for next steps include the following:

1. Continue additional lab-based testing with additional engineered targets
2. Obtain core samples and assess thermography sensitivity to various factors/material property variations
3. Assess the limits of depth of sensitivity of active PT and PPT techniques
4. Further assess the usability and limitations of specific hardware already available to Reclamation (e.g., the Flir Vue Pro UAS IR camera)
5. Purchase more advanced Flir image processing software “Thermal Studio” for batch exporting of images
6. Identify field-scale structures and area office partners that are candidates for field testing of ambient PT, and carry out large-scale imaging on select structure(s).
7. Further develop data analysis and modeling software to provide quantitative material and defect properties (e.g., density estimation) on a pixel-by-pixel basis.

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