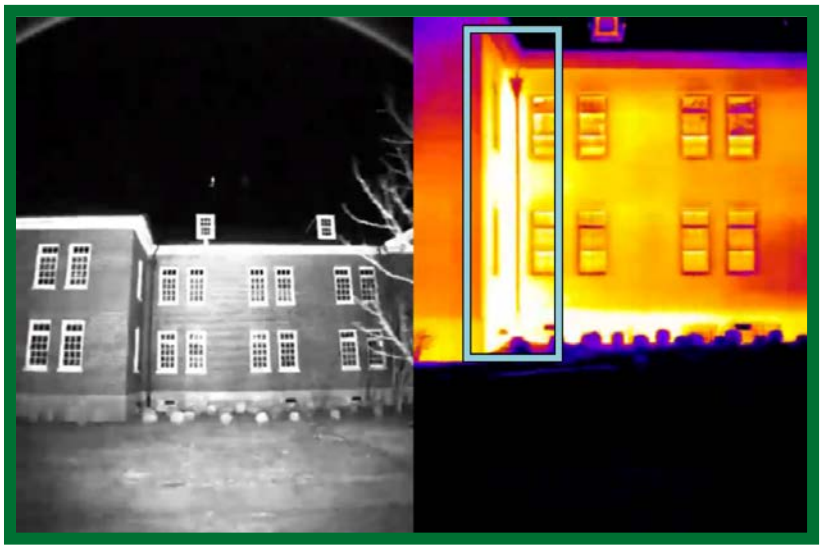
ESTCP
Cost and Performance Report

(EW-201241)



Kinetic Super-Resolution Long-Wave Infrared (KSR LWIR) Thermography Diagnostic for Building Envelopes

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ESTCP

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TECHNOLOGY CERTIFICATION PROGRAM

U.S. Department of Defense

COST & PERFORMANCE REPORT
Project: EW-201241

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ACRONYMS AND ABBREVIATIONS

3-D	three-dimensional
AFB	Air Force Base
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
AWS	Amazon Web Services
BTU	British thermal unit
CERL	Construction Engineering Research Laboratory
CFL	compact fluorescent lamp
CONUS	continental United States
COTS	commercial off-the-shelf
DoD	U.S. Department of Defense
ECM	energy conservation measure
EISA 2007	U.S. Energy Independence and Security Act of 2007
EO	Executive Order
ERDC	Engineer Research and Development Center
ESTCP	Environmental Security Technology Certification Program
EW	Energy and Water
FLIR	forward looking infrared radiometer
FOV	field of view
GB	gigabyte
GIS	Geographic Information System
GPS	Global Positioning System
HDL	High Definition LIDAR
IR	infrared
KSR LWIR	Kinetic Super-Resolution Long-Wave Infrared
kWh	kilowatt hour
LED	light emitting diode
LIDAR	light detection and ranging
LTE	Long Term Evolution
LWIR	long-wave infrared
MIPR	Military Interdepartmental Purchase Request
MIT	Massachusetts Institute of Technology

ACRONYMS AND ABBREVIATIONS (continued)

NIR	near infrared
O&M	operations and maintenance
OCONUS	outside the continental United States
ROI	return on investment
SD	secure digital
SLAM	simultaneous localization and mapping
USACE	U.S. Army Corps of Engineers

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EXECUTIVE SUMMARY

OBJECTIVES OF THE DEMONSTRATION

Each year, millions of dollars' worth of energy leaks from the envelopes of U.S. Department of Defense (DoD) buildings due to missing or improperly installed insulation, cracks around doors and windows, thermal bridges in the wall system and many other deficiencies. Identifying the sources of this wasted energy has historically required manual thermal audits that are typically inconvenient, time consuming and prohibitively expensive for large scale energy analysis. At the same time, Federal agencies are under immense pressure to dramatically reduce the amount of energy consumed by their buildings.

This project demonstrated a unique drive-by thermal imaging process that can enable cost effective energy efficiency in building envelopes at a much greater scale than other commercially available techniques of measuring energy loss due to thermally inefficient building envelopes. This solution used a multi-sensor hardware device mounted on the roof of a customized vehicle to rapidly scan hundreds of buildings in a short period of time. The gathered data were processed and analyzed at the Contractor's (Essess, Boston, MA) headquarters to ascertain important building envelope information. This project demonstrated this technology by scanning U.S. Marine Corps Base Camp Lejeune, NC (American Society of Heating, Refrigerating, and Air-Conditioning Engineers [ASHRAE] Climate Zone 3) and Scott Air Force Base (AFB), IL (ASHRAE Climate Zone 4) to determine the amount of energy being lost at each installation due to thermally inefficient building envelopes.

A primary objective of this work was to compare this drive-by thermal imaging process with the conventional thermal imaging process using a handheld infrared camera. The hypothesis was that the drive-by thermal imaging method is much faster, more accurate and more cost effective than traditional handheld thermal imaging methods. Table ES-1 summarizes the performance objectives and the results of this work. The results listed in Table ES-1 show that the drive-by method satisfied its performance objectives for Rapid Scanning and Rapid Analysis with over 100 buildings scanned per hour and the thermographic image data was analyzed at a rate of approximately 327 buildings per hour. This is at least an order of magnitude faster than could be achieved with handheld thermographic methods.

The Contractor team scanned at least six buildings at each installation using a forward looking infrared radiometer (FLIR) i7 handheld thermal camera. The FLIR i-Series cameras are specially designed for building diagnostics and commonly used in residential and commercial thermal audits. The scanned images for these cameras are 140x140 pixels with a 29-degree by 29-degree field of view (FOV). The FLIR i7 camera uses a Spotmeter to detect the maximum and minimum temperatures within an image. The Contractor found that each of the buildings scanned by the handheld method required about 25 minutes of imaging work. Part of the extra effort involved in this method is the necessity to manually overlap building components in each frame.

No effort was made to analyze the thermal image data captured by the handheld camera because such an analysis would have required all images to be stitched together, which would have been a prohibitively time consuming effort and would have yielded somewhat uncertain results since they would have required a good deal of analyst interpretation.

By comparison, the Contractor's Kinetic Super-Resolution Long-Wave Infrared (KSR LWIR) method uses an integrated camera system that captures 640x512 pixels per frame for a 45-degree x 37-degree FOV. Computer vision calculates the temperature of each feature within the image and obtains material emissivity. Using the KSR LWIR drive-by method, it took about 30 seconds to scan each of the 12 buildings (i.e., six buildings at each installation) in the set that were also scanned by the handheld method.

Table ES-1 lists a number of the more significant performance objectives of this project including metrics, data requirements, success criteria and results.

Table ES-1. Summary of performance objectives.

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives				
Rapid scanning	Buildings scanned per hour	Number of Buildings scanned and required time	> 100 Buildings per hour	*Scott AFB:* 327 buildings scanned at ~ 109 buildings scanned per hour *Camp Lejeune:* 1,307 buildings and other objects (objects being sheds and unmanned buildings) scanned at a rate of ~ 110 objects per hour
Rapid analysis	Buildings per hour	Number of Buildings analyzed and required time	> 50 Buildings per hour	~ 327 buildings per hour for both Scott AFB and Camp Lejeune
Cost effectiveness	Cost ($) for square footage of building scanned and analyzed/ reported	Scanning, analysis and reporting costs for various numbers of buildings, similar costs for handheld methods	Cost below handheld methods for scanning 1M square feet of building space or more, Simple payback = 10 years. (Since buildings can vary from a few hundred to several thousand square feet, total building square feet was used as a metric to measure the cost effectiveness of handheld versus mobile thermal imaging)	*Scott AFB:* Handheld thermography audits would have cost an estimated $920,000 based on 4.6M square feet scanned. Essess costs for Scott AFB were ~ $200,000. *Camp Lejeune:* Handheld thermography audits would have cost an estimated $840,000 based on 4.2M square feet scanned. Essess costs for Camp Lejeune were approx. $200,000

TECHNOLOGY DESCRIPTION

A multi-sensor hardware device is attached to the roof of a customized vehicle to rapidly scan hundreds of buildings in a short period of time. The gathered infrared imagery data are merged with Light Detection and Ranging (LIDAR) data, Geographic Information System (GIS) data, and Global Positioning System (GPS) data and are then processed and analyzed at Essess headquarters to ascertain important building envelope information.

DEMONSTRATION RESULTS

At Scott AFB, over 3,000 distinct building feature components (doors, windows, soffits, etc.) were identified on buildings across the base. These features were categorized by type (e.g., brick wall, roof, window glass, window frame) and surface temperature to provide an in-depth analysis of each building's envelope energy profile. The full Final Report includes an in-depth analysis of 30 thirty buildings with a breakdown of recommended energy conservation measures (ECM) and the potential return on investment. This analysis showed over $300,000 in potential envelope-related savings per year that could be achieved by implementing various envelope-related ECMs. Over the lifetime of the measures, Scott AFB has the potential to save over $4M by investing around $2M with a simple payback period of roughly 7 years.

At Camp Lejeune, over 2500 distinct building feature components were identified across various buildings throughout the base. Similar to Scott AFB, these features were categorized by type and surface temperature to provide an in-depth look at each building's envelope efficiency. This report also includes a detailed thermal analysis of 30 buildings from Camp Lejeune with a breakdown of the most notable leaks for each building and remediation recommendations. This quantified analysis showed that Camp Lejeune could save over $100,000 per year by implementing ECMs outlined in this report. The total investment would be less than $1M, but would allow the base to save nearly $1.7M over the lifetime of the measures with a simple payback period of less than 9 years. The analysis assumes a cost per kWh of $0.056 and cost per therm of $0.59 for both installations.

The Contractor team found that commercial energy audits that include envelope thermal imaging using handheld thermography typically cost around $0.20/square feet (sq ft) of building area (based on data from local thermal imaging auditors within 100 miles of Scott AFB and Green-Buildings.com). Based on the area of buildings scanned at Scott AFB (4.6 million sq ft) and Camp Lejeune (4.2 million sq ft) using the drive-by method, it would have cost approximately $920,000 and $840,000, respectively, using the handheld method.

Essess' costs to scan, analyze and report results for each installation was ~$200,000 regardless of actual square footage scanned. By comparison, the drive-by thermal imaging was found to be much more cost effective than handheld scanning methods.

IMPLEMENTATION ISSUES

Although both Scott AFB and Camp Lejeune have a positive return on investment (ROI), this research shows that Scott AFB has a higher potential savings threshold. This is partially due to the fact that Scott AFB is located in ASHRAE Climate Zone 4 while Camp Lejeune is in ASHRAE Climate Zone 3. Increasing ASHRAE climate zone numbers indicate colder climates. The long term vision of this work is to help DoD reach its goal of saving energy across all military installations by identifying the best candidate installations for energy-saving improvements to building envelopes, i.e., those with the highest potential savings. It would be possible to combine that priority list with information on optimal building stocks and portfolios of cost effective improvements to equip DoD to save millions of dollars in annual energy losses.

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1.0 INTRODUCTION

This project demonstrated a capability to quickly diagnose the condition and thermal performance of building envelopes using Kinetic Super-Resolution Long-Wave Infrared (KSR LWIR) thermography to help the U.S. Department of Defense (DoD) identify and implement opportunities to improve the thermal performance of its existing building inventory. The work was conducted at two DoD installations: Camp Lejeune, NC, and Scott Air Force Base (AFB), IL. It demonstrated a method of rapidly scanning and analyzing many facilities in a few hours, which proved to be far more efficient than current methods, which involve manual infrared (IR) thermographic scanning and analysis of facilities. This method produced an accurate and actionable assessment of the assessed installations' facilities that allowed Facilities Engineers to optimize use of their limited funds to repair or upgrade building envelopes to reduce installation energy consumption.

1.1 BACKGROUND

Many installations have used IR thermography as a tool to help identify buildings that have significant energy leakage through the building envelope and to pinpoint specific problems on existing building envelopes that might be good candidates for repair or improvement. The U.S. Army Corps of Engineers (USACE) requires IR scanning of newly constructed buildings before turnover to the customer. Although the current state of the handheld thermography technology produces reasonably good results, it is very time consuming to implement. Due to the number of facilities at most DoD installations, it would be a formidable task to scan more than a small fraction of the facilities. Post-scanning analysis is also very time intensive and very much dependent on the skill of the individuals operating the IR thermography camera and interpreting the data. As a result, handheld IR scanning and analysis methods are too time consuming, not cost effective for large numbers of buildings, and may yield questionable results.

This project demonstrated a capability that will enable Facility Engineers to cost effectively perform and analyze thermal scans of their installations to identify and prioritize candidate buildings that might benefit from building envelope repairs/improvements. The resulting data will help the installations to improve the energy performance of their facilities, reduce energy consumption and utility costs, and meet mandated energy reduction goals.

1.2 OBJECTIVES OF THE DEMONSTRATION

The objectives of this demonstration were to:

- *Validate:* This project validated a method of rapidly and cost effectively scanning and analyzing large numbers of building envelopes, quantifying energy losses, and prioritizing the remediation of energy leaks for cost effective repairs or improvements. The demonstrated method proved to be more cost effective for performing IR thermal imaging of a large number of buildings than traditional handheld thermographic methods.
- *Provide Findings and Guidelines:* This project demonstrated a process by which Facilities Engineers can cost effectively evaluate large portions of their building stock

to determine the overall condition of their building envelopes and identify opportunities to repair or improve building envelopes to reduce unnecessary energy losses and improve overall energy efficiency. Results are briefly provided in this summary report and fully documented in the Final Report.

- *Accomplish Technology Transfer:* The Essess imaging rig was deployed based on a licensing model so there was (and will be) no turnover of hardware, software, or intellectual property to the Government. Nevertheless, technology transfer will occur through the publication of this report, related Engineer Research and Development Center (ERDC) Technical Reports, and an article in a suitable facilities-related publication. It is anticipated that this published information will enable DoD installations to directly contract Essess to avail themselves of this demonstrated capability.
- *Facilitate Acceptance:* This technology is currently marketed as a service to the utilities industry. Similarly, this technology is a useful tool that can help military installation Facilities Engineers identify thermally inefficient building envelopes that would benefit from remediation, evaluate the effectiveness of building repair and renovation projects, and determine if the energy performance of new buildings complies with design requirements.

1.3 REGULATORY DRIVERS

Facilities Engineers face a major challenge of complying with numerous Executive Orders (EO), statutes, and DoD/Service policies that mandate reductions in energy consumption in a business climate of reduced installation budgets and manpower. Use of this demonstrated technology may help Facilities Engineers comply with the following regulatory drivers:

- *EO 13423. (2007). Strengthening Federal Environmental, Energy, and Transportation Management.* This EO requires Federal agencies to reduce energy use by 20% below their 2003 baseline energy consumption. Reduced energy losses through building envelopes will help installations move toward their energy reduction targets.
- *EO 13514. (2009). Federal Leadership in Environmental, Energy and Economic Performance.* This EO mandates that all new construction, major renovations, or repairs/alterations of Federal buildings comply with the implications of The Guiding Principles for Federal Leadership in High Performance and Sustainable Buildings (Guiding Principles). The Guiding Principles focus on the following five topic areas for both new construction and major renovations:
    1. Employ integrated design principles (new construction)/Employ integrated assessment, operation, and management principles (existing buildings).
    2. Optimize energy performance.
    3. Protect and conserve water.
    4. Enhance indoor environmental quality.
    5. Reduce environmental impact of materials.

Of these topic areas, the first two might be applicable if the results of a thermographic survey provided an impetus to execute a major renovation of one or more existing buildings.

- *Energy Independence and Security Act of 2007 (EISA 2007):* Requires Federal agencies to conduct and document an energy survey of 100% of their "covered facilities" every 4 years. Although a thermographic survey by itself would not satisfy the EISA 2007 energy survey requirements, it would improve the overall quality of an EISA 2007 survey by providing a quality assessment of the condition of building envelopes.
- *Army Directive 2014-02 (Net Zero Installations Policy):* Requires all permanent Active Army, Army National Guard and U.S. Army Reserve installations within the continental United States (CONUS) and outside the continental United States (OCONUS) to "… implement Net Zero to the maximum extent practical and fiscally prudent by reducing overall energy use, maximizing efficiency, …
- *Office of the Chief of Naval Operations Instruction 4100.5E (June 2012):* Requires Navy shore facilities to achieve 30% energy intensity reduction by 2015 as compared with the FY03 baseline and a further reduction to 50% of the FY03 baseline by 2020, at which time 50% of Navy installations must be net zero energy consumers.
- *The U.S. Air Force Energy Strategic Plan (March 2013):* States that the Air Force is pursuing a net zero posture for installation energy and water to help achieve the Federal goal of zero net energy by 2030 for all new facility construction and alterations.

Use of this technology may help Army, Navy, and Air Force Facilities Engineers to reduce overall energy use and maximize energy efficiency by identifying and remediating significant energy leaks in existing buildings as part of their operations and maintenance (O&M) program. It may also help installation planners by helping them recognize buildings with such poor building envelopes that a major renovation or outright replacement of the building would be warranted.

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2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY OVERVIEW

2.1.1 Description

The KSR LWIR drive-by thermal scanning system uses specially equipped vehicles driving on streets and roadways to capture and record multiple data streams representing the surrounding environment. These simultaneously recorded data streams include LWIR thermal video, NIR video, light detection and ranging (LIDAR) three-dimensional (3-D) point cloud mapping data of the vehicle's physical surroundings, Global Positioning System (GPS) vehicle location data and air, and ground surface temperature data. The actual imaging system consists of a custom-designed, multi-sensor rig integrated onto the roof of a scanning vehicle. As the scanning vehicle drives, the imaging rig captures the scene on both sides of the car, enabling the system to image large geographic areas each night. The thermographic video images and other data are stored on board the vehicle using a custom-built data-recording system, and are then processed at Essess' headquarters in Boston, MA.

In an IR thermal image, the brightness of an area indicates its relative energy loss. The brighter the area, the more energy is escaping. Common image patterns demonstrating substantial energy waste include bright yellow lines where siding meets the roof or a chimney, bright yellow or orange auras near the foundation, and yellow auras or lines along window or door edges or around soffits. By contrast, a properly insulated building area will appear darker than the surroundings, most commonly blue or purple.

After scanning, the data are uploaded to the Amazon Web Services (AWS) servers housed in nondescript facilities. AWS data centers have industry leading security to ensure the data are protected by military grade perimeter control with state of the art intrusion detection systems.

Essess performs a number of checks to validate and verify the quality of the scan data. These data streams are then compared to Geographic Information System (GIS) data provided by the installation enabling Essess to accurately locate and identify the scanned buildings. Computer vision algorithms are used to identify and isolate distinct building features (doors, windows, soffits, corners, etc.) and heat loss algorithms analyze and interpret IR imagery pixel by pixel to locate, characterize and quantify major heat losses through the building envelopes.

Essess provides a report including photo imagery (both NIR images and LWIR images) of the scanned buildings that qualitatively locates and illustrates major energy leaks. Essess is then able to perform an analysis and prepare a report that quantifies potential annual energy savings (kilowatt hour [kWh], Therms, and energy dollars) that could be realized by remediating significant sources of envelope heat losses for each building. The report also estimates the remediation costs and provides simple payback periods and returns on investment (ROI) for each remediation category for each building (e.g., improve wall insulation, seal window frame leaks, improve soffit insulation, etc.).

2.1.2 System Components

The drive-by thermal imaging vehicles are equipped with the following components/capabilities:

- A multi-spectral IR imaging system, which includes:
  - LWIR radiometric cameras
  - NIR high dynamic range cameras
  - NIR scene illumination for rural and poorly lit suburban regions
  - Capture of thermal signatures of structures
  - Discovery of building facades and background removal using computer vision and machine learning engines
  - Camera housing offering a 70-degree vertical field of view (FOV) and a full width horizontal FOV of structures due to vehicle motion.
- An automated building detection capability within property boundaries, including:
  - Rotating laser array LIDAR sensor to capture ranging and reflectance even from large standoff distances
  - Isolation of buildings from the surrounding scene using 3-D LIDAR point clouds
  - Ranging capability allowing structures to be bounded within property lines and relevant locations
  - Mapping grade GPS and support filtering algorithms to ensure accurate location of structures and properties
  - Collected data for use in simultaneous localization and mapping (SLAM), allowing the system to supplement the captured GPS data and more accurately correlate each image to the relevant building.
- A highly reliable onboard data capture and diagnostics system, which includes:
  - A system that performs over a wide range of seasonal temperatures, down to at least -30°C and up to above 40°C
  - A high mast that enables operation in a variety of regions, including short standoff distances with 3-4 story buildings
  - Onboard data validation and recording software and hardware
  - Real-time diagnostic and quality control capability provided by streaming communications with Essess headquarters over an Long Term Evolution (LTE) cell network.

Combined, these hardware and software capabilities constitute a highly effective way to capture heat loss and building envelope data via a drive-by thermal imaging rig as shown in Figure 1. Each camera captures data in a video format, meaning that the drive-by system generates hundreds of thousands of images comprising over 2 terabytes of data in a typical night of scanning. The LIDAR sensors enable the system to generate a 3-D map of the physical

environment and map buildings to parcels in a highly accurate manner. Figure 2 shows an enlarged image of Essess' integrated scanning system. Figure 3 shows a schematic outline of Essess' proprietary thermal imaging system.

Figure 1. Specially equipped Essess scanning vehicle.

Figure 2. Contractor-developed scanning rig including GPS, LWIR, NIR and LIDAR instrumentation.

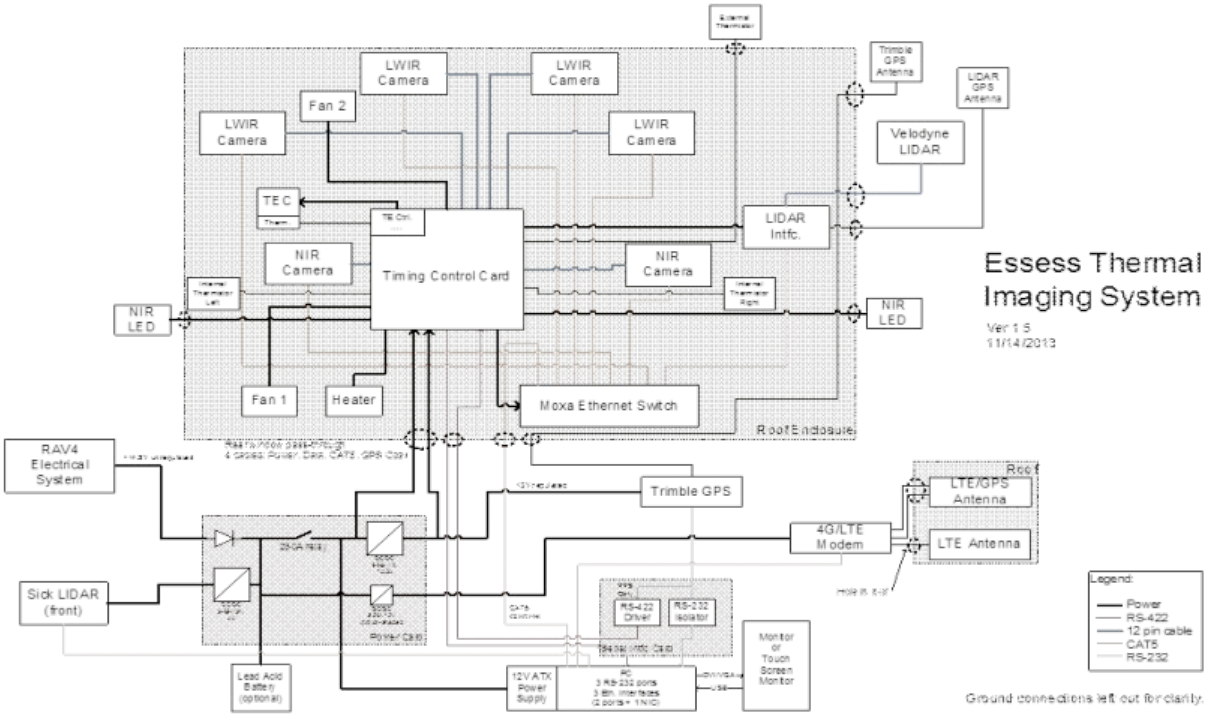

Figure 3. Schematic outline of the proprietary Essess Thermal Imaging System.

2.1.3 Technology Development

The system hardware, comprised of the physical sensors on top of the vehicle, and the software which processes and analyzes the collected data are both based on research conducted at the Field Intelligence Lab at the Massachusetts Institute of Technology (MIT). Dr. Sanjay Sarma, Professor of Mechanical Engineering, recruited leading scientists and thought leaders to study the viability of remote, high-throughput thermal imaging at scale and develop techniques for identifying and assessing energy waste on a large scale. The practical applications of high-throughput thermal imaging were researched and studied for multiple years before a prototype was built. The first imaging rig was tested in Cambridge, MA, and the data were analyzed to create a heat map overview of the city. The rapid scanning methodology and processing of imaging data were also demonstrated at Fort Drum, NY, in February 2011. Further research and development produced the current imaging rig, which uses cutting edge technology to gather terabytes of data on a typical night of scanning. The custom hardware is augmented by advanced software algorithms to efficiently process the data.

This Environmental Security Technology Certification Program (ESTCP) project evaluated the application of this technology at two military installations. No hardware or software development was conducted during this project. It is anticipated that long term application of this technology will help DoD reach its goal of saving energy across all military installations by identifying the best candidate installations for energy-saving improvements to building envelopes.

2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

2.2.1 Performance Advantages

This technology may improve energy efficiency by enabling Facilities Engineers to cost effectively scan and analyze most or all of the building envelopes on their installations to identify and prioritize the most significant energy leaks and to implement measures that repair or improve the building envelopes. With handheld thermography methods, it would be much too costly and time consuming to perform IR scans and analyze the data for large numbers of buildings.

2.2.2 Cost Advantages

For large sets of buildings, this technology should be much more cost effective than traditional handheld methods of performing IR thermography scanning and analysis of buildings. Handheld IR scanning methods and subsequent data analysis by a human are much more time consuming, resulting in significant added labor costs.

2.2.3 Performance Limitations

This technology is limited to scanning the street sides of buildings. As a result, for most buildings, four sides of the building cannot be scanned. Two or three sides are commonly scanned depending on the orientation of a building relative to the street. This technology is also limited by the requirement to have a ΔT between building interior and exterior ambient temperatures of at least 20°F, so scanning must occur when nighttime temperatures are below

50°F. This limits application of this technology to regions where there is at least 1 week of the year in which nighttime temperatures are below 50°F. Most regions of the United States fall within this boundary condition. Adjustments are made for empty buildings or buildings where there is no internal heating and no way of knowing the internal temperature setpoint. This technology is somewhat hindered by trees, bushes and other obstructions that might partially obscure a clear view of a building's envelope from the street. However, the automated data processing pipeline developed by Essess, which takes the scanned data and prepares it for report format, corrects for these kinds of obstructions in a number of ways that have been tested and validated.

2.2.4 Cost Limitations

There is a lower limit of the number of buildings that can be cost effectively scanned and analyzed by this method. Below this limit, it is more cost effective to identify and analyze building envelope energy leaks by another method. This demonstration sought to determine this cutoff point. As referenced in Table 1, "Summary of Performance Objectives," the average cost for performing a handheld thermal audit on a 5,000 sq ft commercial building is approximately $1000. Considering Essess charges approximately $200,000 per installation for its services, it is beneficial to perform an Essess scan for any installation that has at least 1 million sq ft in its building inventory (determined by adding the individual square footage of each building scanned). To put this in perspective, over 4.6 million sq ft and 4.2 million sq ft of buildings were scanned at Scott AFB and Camp Lejeune, respectively.

It is also important to document the cost of this technology application to help Facilities Engineers determine how the technology might enhance their business processes. For example, this technology can scan and capture data pertaining to hundreds, even thousands, of buildings in a very short period of time. Very large installations could be scanned within a matter of days. The resulting marginal cost of scanning buildings is relatively small. However, the process of analyzing scan data to identify and prioritize energy leaks is more challenging and has a significantly higher marginal cost. Both of these processes must be done together to provide the military base with actionable results. It follows that any documentation of the cost of this technology application that will help Facilities Engineer determine how they might benefit from Essess' thermal imaging process must clearly account for the costs of both these services.

2.2.5 Social Acceptance

There were no problems associated with social acceptance by installation staff. This technology had little or no impact on the activities or processes of the host installations. On-site activities were conducted at night when very few installation operations were occurring. The only burden placed on installation personnel was the need for them to provide installation GIS data and energy data for analysis requirements.

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3.0 PERFORMANCE OBJECTIVES

Table 1. Summary of performance objectives.

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives				
Rapid scanning	Buildings scanned per hour	Number of Buildings scanned and required time	> 100 Buildings per hour	*Scott AFB:* • ~ 109 buildings per hour for a total of 327 buildings (Based on building density of Scott AFB, rig set-up and resting period. Total imaging time of 3 hr, 0 min with 52 min of rig set-up, calibration, travel time, and resting period.) *Camp Lejeune:* • ~ 110 buildings per hour scanned. • 1,307 buildings and other objects (e.g., sheds, lamps, and other unheated structures) were scanned. Total imaging time was 11 hr, 54 min after adjusting for various delays including inclement weather.
Rapid analysis	Buildings per hour	Number of Buildings analyzed and required time	> 50 Buildings per hour	~ 327 buildings per hour for both Scott AFB and Camp Lejeune (leaks identified as polygons and subsequently analyzed)
Actionable results	Building envelopes determined to be adequate (needing no improvements) or improvement projects scoped for envelopes having identified deficiencies	Number of envelopes deemed adequate and/or having projects scoped to correct identified deficiencies	For each installation, the envelopes of at least 25 of the 30 buildings selected for detailed analysis are deemed to be adequate or have projects identified to correct deficiencies	*Scott AFB:* • 392- Window Frames • 97- Door Frames • 686- Walls • 170 – Roofs • 241- Soffits *Camp Lejeune:* • 1,037 - Window Frames • 201 - Door Frames • 412 - Walls • 232 - Roofs • 329- Soffits
Cost effectiveness	Cost ($) for square footage of building scanned and analyzed/reported.	Scanning, analysis and reporting costs for various numbers of buildings, similar costs for handheld methods	Cost below handheld methods for scanning 1million sq ft of building space or more, Simple payback = 10 years. (Since buildings can vary from a few hundred to several thousand square feet, total building square feet was used as a metric to measure the cost effectiveness of handheld versus mobile thermal imaging methods)	*Scott AFB:* Handheld thermography audits would have cost an estimated $920,000*. Essess costs for Scott AFB were approx. $200,000. *Camp Lejeune:* Handheld thermography audits would have cost an estimated $840,000 based on 4.2 million sq ft scanned. Essess costs for Camp Lejeune were approx. $200,000

Table 1. Summary of performance objectives (continued).

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Qualitative Performance Objectives				
Robust technique within defined range of operating conditions	High quality scanned imagery	Scan data quality under a range of environmental operating conditions	"High Confidence**" in results obtained within defined limits	Success: Within the defined range of operating conditions, the thermal imaging system is capable of capturing high quality data that can be analyzed for envelope issues.
Comparing the fidelity and usefulness of imagery at various scanning distances	Measuring the image quality of data taken at varying distances starting at 20 yds and ending at 180 yds with 20 yd intervals	Thermal images taken by mobile imaging rig at 20 yd intervals from 20 to 180 yds	"High Confidence"** that the temperature data can be seen at extreme distances	The results show that IR imaging is capable of capturing temperature data at 180 yds. However, the number of pixels in the frame limits the data quality.
Street-side scanning sufficient	Representativeness of street-side sample versus 360-degree scan of building using handheld methods	Street-side drive-by scan results, 360-degree handheld scan results	"High Confidence"** that results of street-side scans adequate for planning purposes	Street-side data is representative of sides not seen from the street
Ability to usefully scan Bldgs obscured by wall of trees and other obstructions	Data loss due to obstructions	Leaks obscured by obstructions	"High Confidence" that obstructions do not appreciably impact results	Line-of-sight between imaging system and building is required for data capture. The imaging rig is able to capture data when driving by a single tree or utility pole, but is unable to capture data when the building is completely blocked from the imaging rig (i.e., with a fence, multiple trees, etc.). This was previously tested while the technology was in research and development.

* Commercial energy audits that include envelope thermal imaging using handheld thermography can typically cost around $0.20/sq ft of building area (based on data from thermal imaging auditors within 100 miles of Scott AFB and Green-Buildings.com). At Scott AFB, Essess imaged 4.6 million sq ft and 278 buildings. Unlike a typical auditor that charges per building, Essess' cost structure is on a per installation basis. This is due to the fact that the bulk of Essess' costs are front-loaded. Once the imaging rig is deployed to an area, there is only a marginal cost in imaging 1,000 buildings versus 100 buildings.

** "High Confidence" is a visual examination by an Essess scientist resulting in a determination that the data can be used for performing an analysis of the building envelope.

4.0 FACILITY/SITE DESCRIPTION

4.1 FACILITY/SITE LOCATION AND OPERATIONS

Scott AFB, which is located approximately 20 miles east of St. Louis near Belleville and O'Fallon, IL (Figure 4), is the home of the 375th Air Mobility Wing providing mission-ready Airmen and capabilities. Scott AFB has a broad range of facility types and a full spectrum of facility vintages from very old to very modern.

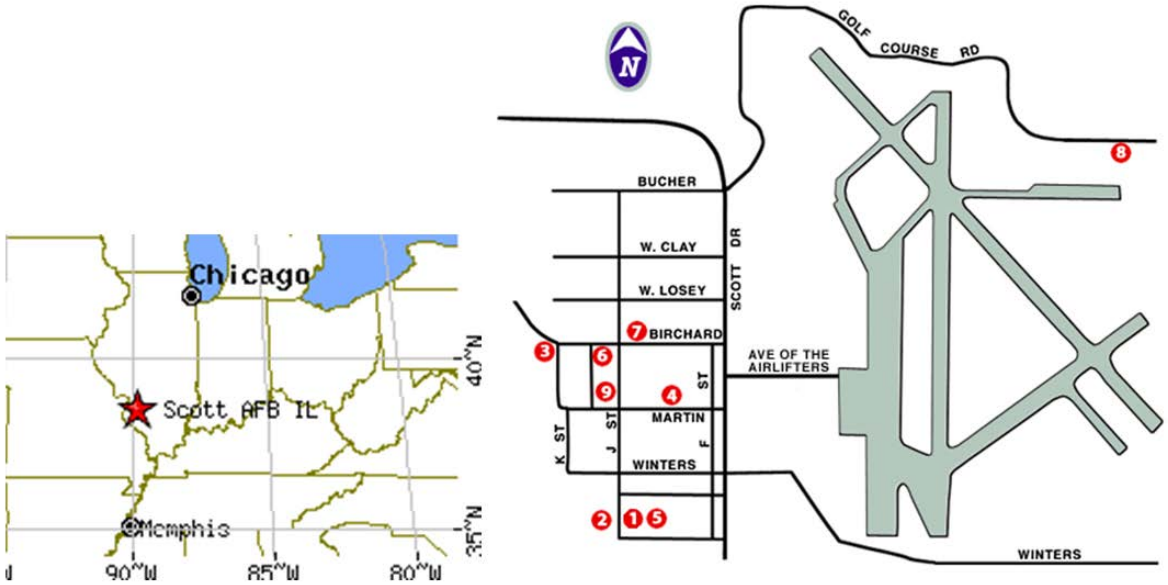

Figure 4. General location (left) and installation map (right) of Scott AFB.

Camp Lejeune is a 246-sq-mi U.S. Marine Corps training facility located along the Atlantic Coast in Jacksonville, NC (Figure 5). The main base is supplemented by five satellite facilities: Marine Corps Air Station New River, Camp Geiger, Stone Bay, Courthouse Bay, Camp Johnson, and the latest addition to the facility, the Greater Sandy Run Training Area.

Camp Lejeune is the largest Marine base on the East Coast. The base's 14 miles (23 km) of beaches make it a major area for amphibious assault training, and its location between two deep-water ports (Wilmington and Morehead City) allows for fast deployments.

Figure 5. Location of Camp Lejeune, NC.

Since the on-site activities associated with this demonstration were very short term, there was little or no interaction between this project and normal military activities at either installation.

4.2 FACILITY/SITE CONDITIONS

The mobile scanning technology is relevant to American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Climate Zones where the heating season ΔT (indoor to outdoor temperature) can be expected to be at least 20°F during the building scanning period. As a result, this technology may not be applicable to certain regions within Climate Zones 1 and 2. Nevertheless, the technology is capable of capturing data during the cooling season as long as the ΔT (indoor to outdoor temperature) is 20°F.

This demonstration selected installations in Climate Zones 3 and 4 that had a large number of significant buildings from which to select. Scott AFB and Camp Lejeune are large installations with a full range of facility types and buildings of various vintages. This demonstration worked with the installations to select buildings typical of other modern DoD installations. Buildings selected included command headquarters, dormitories, training facilities, admin facilities and similar large buildings. At each installation, a minimum of 250 buildings were scanned and a detailed analysis of 30 installation-selected buildings was performed.

5.0 TEST DESIGN

5.1 CONCEPTUAL TEST DESIGN

5.1.1 Hypothesis

The hypothesis of this demonstration was that Essess' drive-by thermal imaging method gathers and analyzes building envelope energy efficiency information from the building stock in a manner that is faster, more cost effective, and easier to scale than via traditional handheld thermographic methods.

5.1.2 5.1.2 Independent Variable

The main independent variable being tested was the type of thermal scanning technique which was the KSR LWIR imaging and analysis process as compared to conventional thermal scanning using a handheld camera followed by human processing of the handheld thermal imagery.

5.1.3 Dependent Variable(s)

Measured dependent variables included emissivity, building type, building square footage, and scene occlusion. Other variables tested during the demonstration process included:

- Scanning time (scanning time using a mobile imaging system versus scanning time using a handheld thermal camera to determine scalability in terms of time)
- The effects of resolution when scanning with the imaging rig versus scanning with a handheld camera to determine importance of image quality
- Scanned image quality from varying distances (specifically 20 meters, 50 meters, and 100 meters).

5.1.4 Controlled Variable(s)

Controlled variables included the pre-selection of building types of similar size and building materials for scanning and analysis by both the drive-by and the handheld methods. Both scanning methods were conducted simultaneously to ensure identical temperatures and weather conditions during scanning operations.

5.1.5 Test Design

The demonstration of the KSR LWIR imaging technology took place during February and March 2014. Multiple buildings were scanned at Camp Lejeune, NC, and Scott AFB, IL, using the drive-by thermal imaging rig. Six buildings were scanned at each military installation using both the drive-by scanning rig and a traditional handheld thermal camera to set up the comparative analysis between the two methods of gathering thermal data. The scanning process began 2 hours after sunset and concluded 30 minutes before sunrise on nights with temperatures below 50°F. The imaging rig captured and recorded data on hard drives that were mailed back to Essess headquarters for processing. Images were analyzed with respect to energy loss via infiltration, damaged building components, inadequate insulation, and thermal bridges. The imaging data

was combined with GIS information, LIDAR data, and other building data. Thermal images taken with a handheld camera were not processed by automated methods, but were visually analyzed by a human auditor.

Further tests were done to determine whether the mobile KSR LWIR imaging could collect building envelope efficiency data faster than traditional handheld thermography without compromising the quality of the diagnostic data by customizing the imaging rig specifically for gathering data on a military installation.

5.2 BASELINE CHARACTERIZATION

The following data were collected for each military installation: building and parcel footprints (available for both Camp Lejeune and Scott AFB in the form of GIS polygons), address points, address metadata, energy consumption data (gas and electrical, only available for certain buildings for Camp Lejeune and Scott AFB) for multiple years for each metered building, building vintage (available for Scott AFB, but only partially available for Camp Lejeune buildings), and building size (available for Scott AFB, but only partially available for Camp Lejeune buildings). Data collected by the imaging rig on scanning nights included: ambient temperature, ground temperature, sky temperature, and precipitation levels. Both Camp Lejeune and Scott AFB were able to provide GIS data. Energy data were not available for all buildings scanned at either military installation.

The data for Camp Lejeune were collected over the period of 10-14 February 2014. Scott AFB data were collected over the period of 28 February to 1 March 2014. For both installations, data were collected on nights where the temperature and weather conditions were conducive to thermal imaging. Handheld thermography images were captured on the same nights.

The cost of conventional handheld IR thermography was estimated based on the cost of equipment and the market rate of skilled labor to perform the analysis. Measurements of selected buildings were taken with handheld IR cameras to create a baseline to compare with the results from the vehicle-mounted rig.

5.3 DESIGN AND LAYOUT OF SYSTEM COMPONENTS

5.3.1 System Design

The thermal imaging rig combined several commercial off-the-shelf (COTS) sensors with custom electronics, software and an environmental housing to record data samples:

- Trimble A3000 DR+GPS
- Velodyne High Definition LIDAR (HDL)-32e 3-D LIDAR
- Four FLIR A65 thermal imaging cameras
- Two Allied Vision Technologies Manta G-283B camera
- SICK LMS111-10100 2D LIDAR.

The Trimble GPS along with the front facing SICK LIDAR were used to continuously estimate the position of the scanning vehicle during the scanning process. The Velodyne LIDAR was used

for 3-D reconstruction of buildings and other structures. The Manta cameras were used with the computer vision system to detect NIR features. Thermal measurements were made with the FLIR LWIR cameras. The data produced by these systems were recorded to a mirrored set of hard drives, and were post-processed using computer vision, machine learning, and thermal analysis algorithms to generate actionable envelope intelligence.

5.3.2 System Layout

Figure 6 shows the multi-sensor imaging hardware. The GPS antenna mapped the location of the scanning vehicle, the LIDAR created a dense point cloud to determine the 3-D landscape, the LWIR cameras measured heat, the NIR cameras detected building features similar to what someone might have seen through a night vision camera and the NIR illuminator acted as a floodlight for the NIR camera.

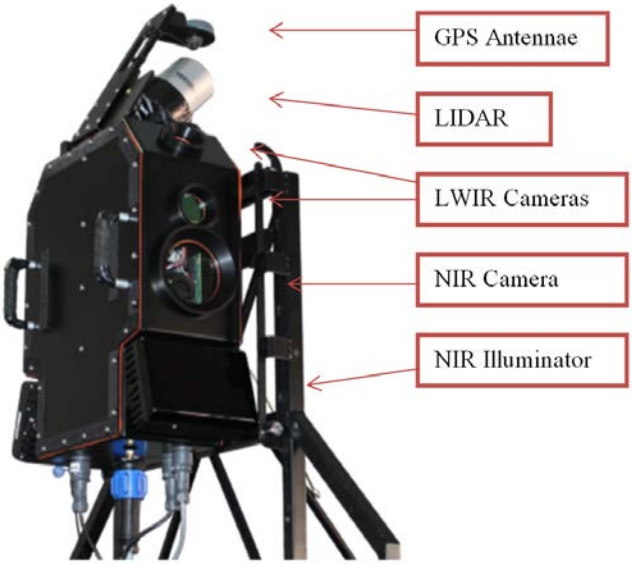

Figure 6. Essess' multi-sensor imaging hardware.

5.4 OPERATIONAL TESTING

Data collection involved driving the imaging rig to a given location and scanning the area based on pre-defined routing tracks. The imaging team waited until sunset to set up the system and then began imaging. This mitigated the effects of solar radiation and allowed the team to capture data at a period with the largest temperature difference (middle of the night). To ensure that high quality data were captured, no imaging took place during precipitation events. Development of an operational testing plan (Phase 1 activities) began in early February 2014. On-site thermal scanning operations (Phase 2 activities) at Camp Lejeune were conducted over the period of February 10-14. This work probably could have been accomplished over a period of 2 nights were it not for a large blizzard that caused the installation to be shut down for 2 days. Scanning activities at Scott AFB were conducted over the evening of 28 February to 1 March 2014. Processing and analysis of data (Phase 3 activities) for both installations occurred during April and May 2014.

5.5 SAMPLING PROTOCOL

Terabytes of thermal imaging, LIDAR and GPS data were collected at each base. For a subset of six of the buildings scanned by the drive-by method, data were also collected using a handheld thermal camera to do a comparative analysis between handheld thermography and drive-by KSR LWIR scanning to determine the efficiency (amount of time taken to scan) and effectiveness (ability to identify energy leaks) of each method. Data were written into 2 gigabyte (GB) files to a mirrored disk array and checksums were generated and stored as metadata to ensure long term data integrity. The data were physically uploaded to a secure, private cloud system and physical hard drives were stored as back-ups at Essess' headquarters in Boston, MA.

5.6 SAMPLING RESULTS

As required, Essess captured drive-by thermal imaging data for at least 250 buildings at each installation and 360º handheld thermographic images for a subset of six of these buildings at each installation. Figures 7 and 8 show handheld thermographic images juxtaposed next to NIR and thermographic images recorded by the drive-by method for a building at Scott AFB and another building at Camp Lejeune.

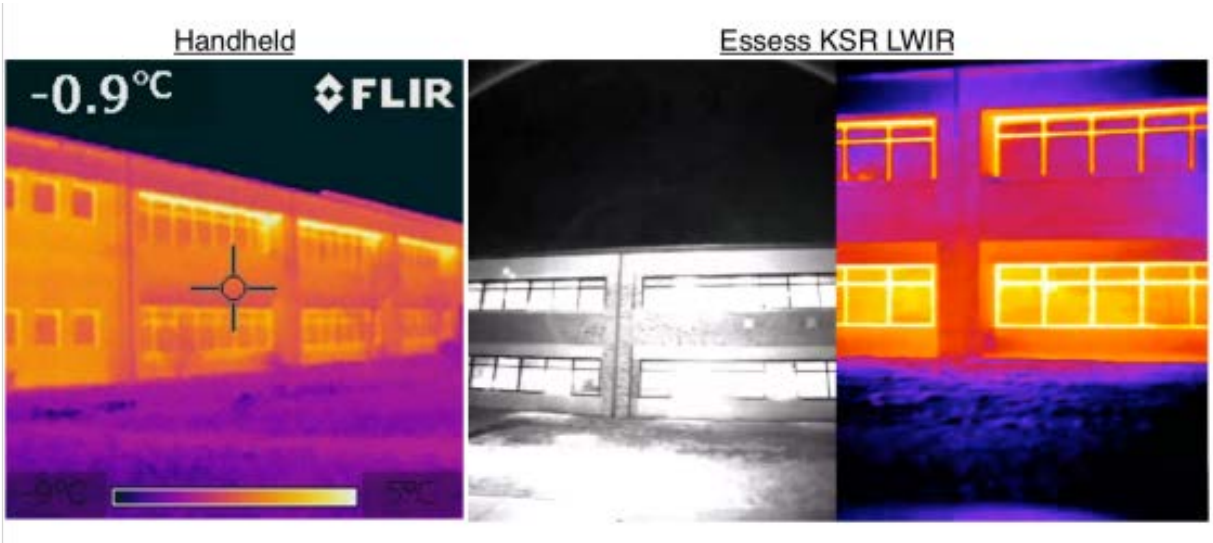

Figure 7. Handheld thermographic image (left) versus the KSR LWIR thermographic image (right) for a building at Scott AFB.

Figure 8. Handheld thermographic image versus Essess KSR LWIR thermographic image for Bldg 235, Camp Lejeune.

The images shown in Figures 7 and 8 offer some useful comparisons between the drive-by thermal imaging method and the traditional handheld approach. Using the handheld method, thermal imagery data are stored on a low speed secure digital (SD) card. Image contrast is tuned for visual use. The center point of reported temperatures is what is outputted to the user. Resolution typically ranges from 80 x 80 pixels to 150 x 150 pixels. The FOV is 30 x 30 degrees. While the handheld imaging method has an advantage in that it has a greater capability to record thermal images around the entire perimeter of almost any building, this work is quite time consuming and requires overlapping of adjacent frames to avoid missing potentially important details. Ultimately, the captured images must be viewed and manually analyzed by a human, which is a laborious task that introduces great possibility for human error. The use cases for these handheld imagers are low throughput, non-quantitative work.

By contrast, the KSR LWIR integrated scanning system uses multiple radiometric thermal cameras. These devices are designed for high-throughput analytical and computer vision work. The devices are configurable through computer control and automation. Data flows from devices over a high speed local network to high speed redundant storage. Raw digital number information is stored for each image frame. Resolution per camera is 640 x 512 pixels. The FOV per camera is 37 x 45 degrees while the total FOV is 37 x 80 degrees.

Images can be acquired at a much faster rate using the Essess sensor system. There is continuous acquisition without the need to manually frame the building. Each video frame contains overlapping information. Further, the raw information allows temperature conversions to be done per individual region in the frames versus just one temperature point as in the handheld instrument. The Essess system also provides NIR images associated with each LWIR image as shown in Figures 7 and 8. This is a very helpful feature which provides the ability to pick out features and textures that may not be easily visible in the LWIR image, as the NIR image is similar to a conventional grayscale photograph.

Essess also tested the impact of distance between the test rig and buildings being scanned upon the usefulness and effectiveness of the captured thermographic imagery. Figure 9 shows IR images of one of six buildings scanned at distances from 20 to 180 yards in increments of 20

yards. The results show that the distance between the cameras and the building appears to have very little effect on the system's ability to measure building surface temperatures. Nevertheless, as one might expect, building feature recognition becomes more difficult as the distance from which a building is scanned is increased and individual building leaks also become gradually less visible as the distance is increased. The obvious conclusion is that "closer is better." In most cases, typical distances from the centerline of roadways of military installations to the façade of buildings on either side of the street should produce acceptable results. In rare instances where buildings are set back extremely far from the roadway, it is often possible to reduce the standoff distance by scanning from nearby parking lots and access roadways.

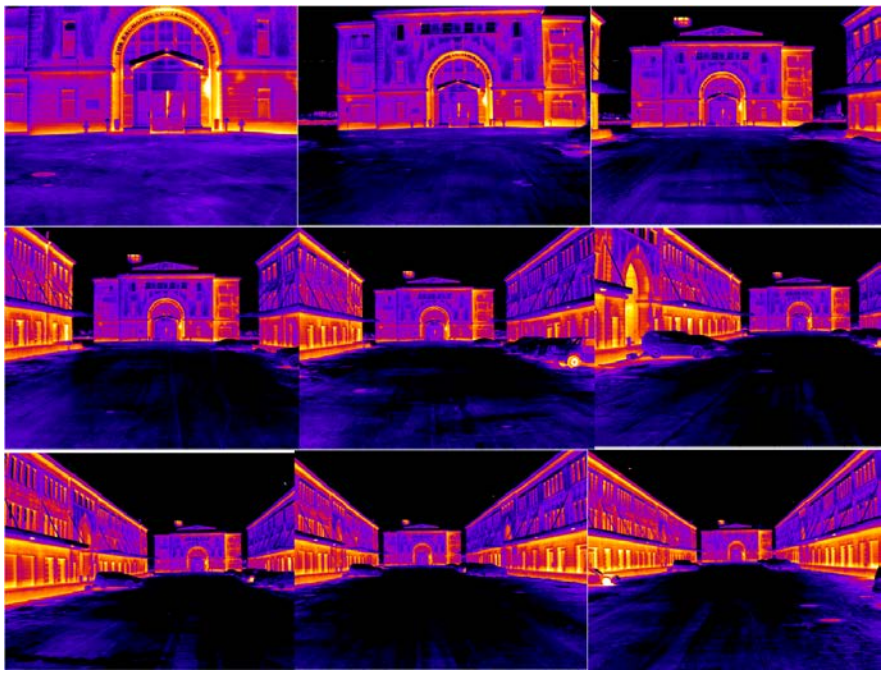

Figure 9. Essess KSR LWIR distance test.
From left to right—Row 1: 20 yards, 40 yards, 60 yards;
Row 2: 80 yards, 100 yards, 120 yards; Row 3: 140 yards, 160 yards, 180 yards.

Of the hundreds of buildings scanned at each installation, the Facility Engineers at each site down selected 30 buildings for Essess' detailed analysis. Results of these detailed analyses for these 60 buildings are provided in Appendix C (Scott AFB) and Appendix D (Camp Lejeune) of the full Final Report. The next section gives a sample of the detailed analysis for Building 1961, Scott AFB.

5.6.1.1 Detailed Analysis for Bldg 1961, Scott AFB, IL

Name: USTRANSCOMM Annex
Use Type: Office
Square Footage: 80,284
Average Daily Electric Use: 5,694 kWh
Average Daily Gas Use: 63.7 therms
Electricity Score: 60th Percentile
Gas Score: 50th Percentile

Annual Cooling Load: 614,284 kWh
Annual Heating Load: 18,071 therms

The electricity and gas scores above compare Bldg 1961 to similarly sized buildings of the same type on an energy use per square foot basis. An energy score at the 100th percentile represents the highest energy use per square foot relative to similar buildings, while a score at the 0th percentile represents the lowest. The annual cooling and heating loads are calculated by regressing natural gas bills and electric bills against degree days for each billing period to disaggregate the heating and cooling components of building energy use.

Bldg 1961 has a gas usage of 28,960 British thermal units (Btu)/sq ft/year and electricity usage of 25.9 kWh/sq ft/yr.

Bldg 1961 serves as an interesting example of how energy use per square foot is not always a good predictor of leakiness or remediation potential. The building is perhaps the most incompletely insulated building among those scanned at Scott AFB, with numerous large hot spots scattered all over the exterior. However, its gas score only puts it in the 50th percentile, meaning that about half the buildings of a similar square footage have higher gas usage per square foot. The electricity use is a similarly middling 60th percentile.

Figure 10 shows an abatement curve for all identified remediation measures for Bldg 1961, Scott AFB. Each bar represents a distinct remediation. The width of the bars represents the savings potential, while the height represents the economic viability (represented by ROI). The height of each bar shows how many dollars of savings may be expected for every $1 spent on that particular remediation measure.

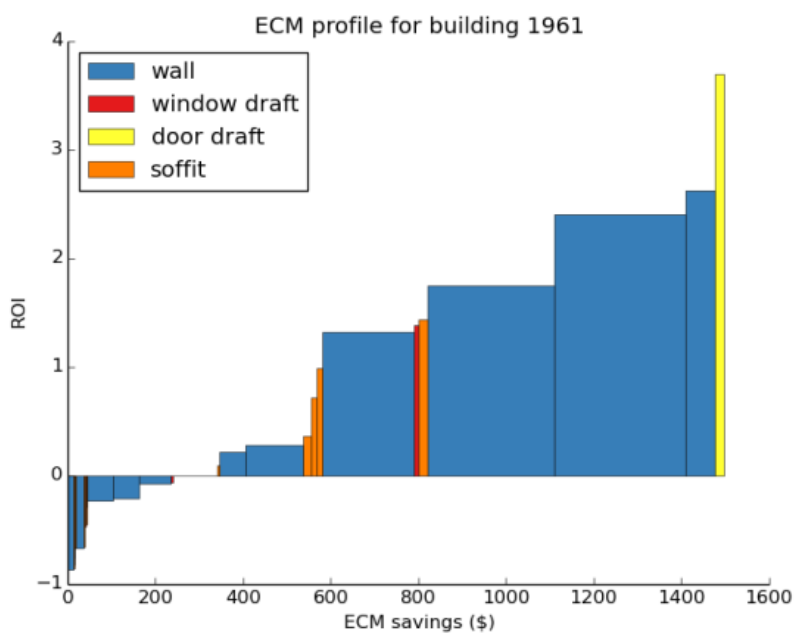

Figure 10. ECM profile for Bldg 1961, Scott AFB.

Table 2 lists the recommended envelope energy conservation measures (ECM) for Bldg 1961.

Table 2. Envelope ECMs, Bldg 1961, Scott AFB.

ECM Name	kWh Saved	Therms Saved	Dollars Saved	Upfront Cost	Payback Period
Improve Wall Insulation	714	1721	1055	6818	6.5
Improve Soffit Insulation	47	114	70	612	8.8
Seal Door Frame Leaks	14	34	21	66	3.2
Seal Window Frame Leaks	7	17	10	66	6.3

Annual potential remediation savings for this building are $1,156 and simple payback is 6.5 years for this package of envelope-related ECMs.

5.6.1.2 Notable Leaks

There is a sizable patch of poorly insulated wall on the second story of the building around timestamp 42:55. The soffit also appears to be highly emissive (Figure 11).

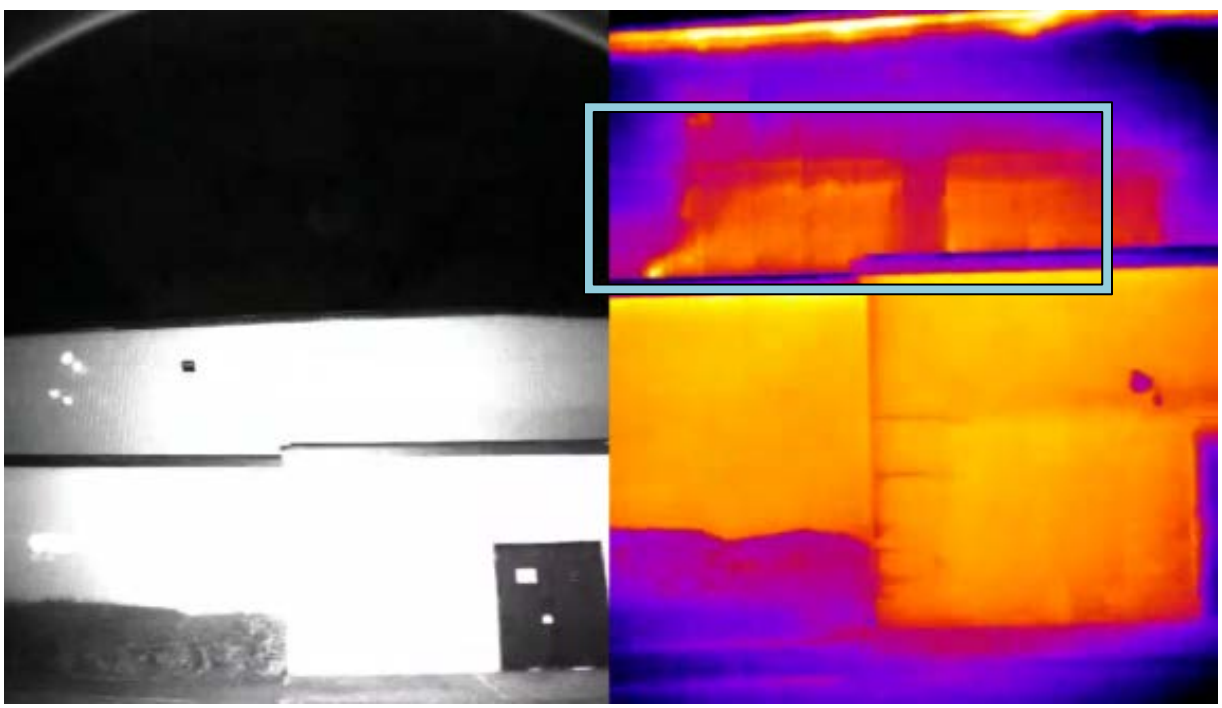

Figure 11. Poorly insulated wall for Bldg 1961, Scott AFB.

There is a sizable patch of poorly insulated wall on the second story of the building around timestamp 42:55 (Figure 12). The soffit also appears to be highly emissive.

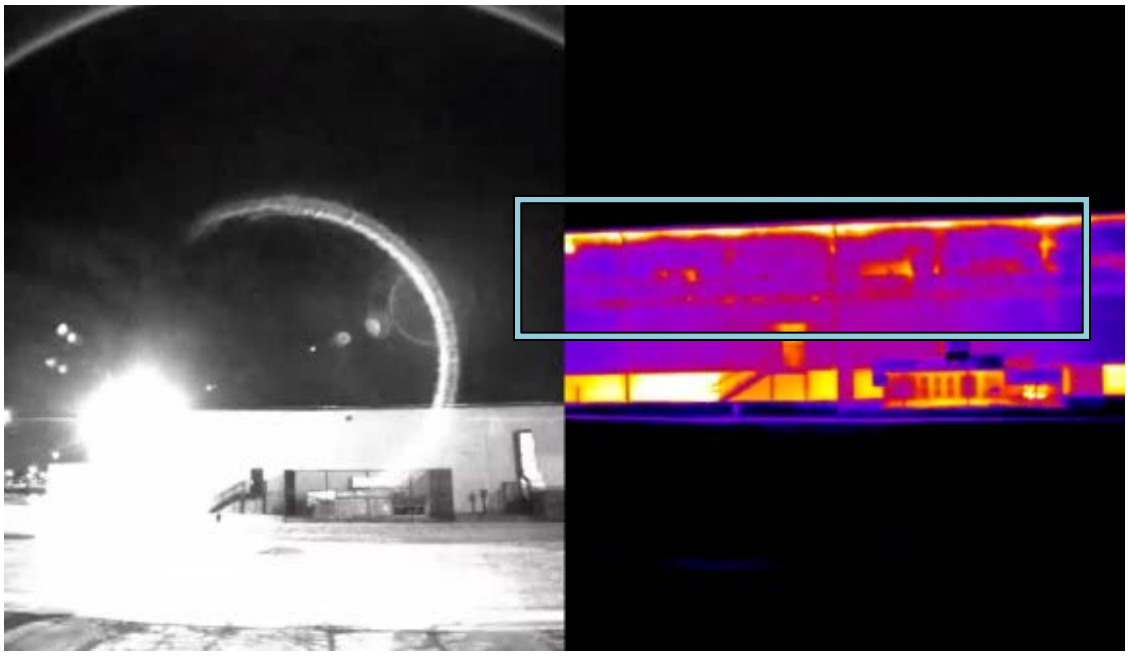

Figure 12. Various wall insulation gaps for Bldg 1961, Scott AFB.

There are numerous wall insulation gaps around the back of the building around timestamp 43:11, as well as a leaky soffit (Figure 13).

Figure 13. Rearview of Bldg 1961, Scott AFB.

The back of the building around timestamp 43:31 is particularly emissive, with large amounts of heat leaking out. The wall has significant insulation issues (Figure 14).

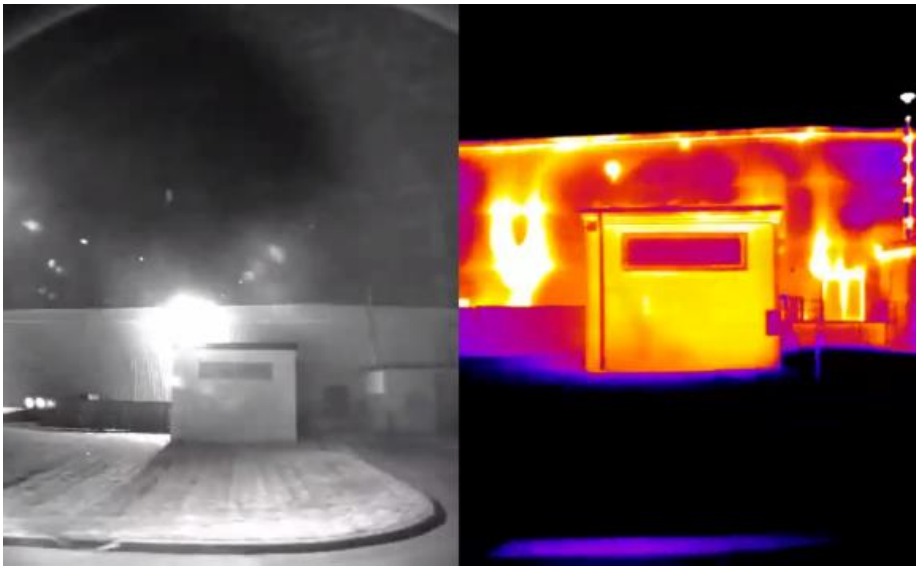

Figure 14. Large wall leaks for Bldg 1961, Scott AFB.

Similar large leaks are seen on the wall at timestamp 43:32. The "patchy appearance" indicates inconsistent insulation throughout the wall. The double doors to the right of the image may also have notable convective leaks around the frame.

5.6.1.3 Portfolio Strategy Analysis for Scott AFB, IL

The Essess team identified 3,263 distinct feature components on 146 different buildings on Scott AFB out of a total of 328 buildings and other objects surveyed. These features were categorized by type (e.g., brick wall, roof, window glass, window frame) and surface temperature. Heat losses were calculated based on the temperatures of the features, the times of observation, the orientations of the features, and the outdoor air temperature. The analysis of Scott AFB thermal imaging data resulted in an estimated $304,393 in potential annual building envelope-related energy cost savings across all buildings on the base for remediation measures that have a payback period of 15 years or less. These savings would require approximately $2,211,500 in capital expenditures for remediation. The recommended measures include retrofitting of walls, soffits, and roof insulation and sealing leaks around windows and doorframes. Implementing these remediation measures could save Scott AFB approximately $4,385,376 over the lifetime of the projects (15 years on average), and the measures would pay for themselves after 7.3 years. The recommended savings are the subset of those with a payback period of 15 years or less, while annual savings reflect all measures with positive savings independent of the remediation costs.

These base-level savings are estimated dividing the calculated savings for each building by the fraction of the building actually imaged, assuming that the portions of the building not imaged are similar in characteristics (R-values, infiltration) to the portion imaged. The area of the buildings captured in the street-view thermal images identified $113,264 in savings from discrete building component leaks, at a cost of $824,985 and with a payback period of 7.3 years. The total savings over the lifetime of the envelope remediation projects identified in the thermal

images was $1,612,845. Table 3 lists the potential savings and payback period for each category of envelope-related remediations for all imaged buildings at Scott AFB.

Table 3. All recommended envelope-related remediations, Scott AFB.

Measure	Potential Savings	Payback Period
Door Frame Leaks	$3,376	2.2
Window Frame Leaks	$8,507	3.2
Basement Wall Insulation	$2,281	7.6
Wall Insulation	$93,905	7.7
Soffit Insulation	$2,582	9.6
Roof Insulation	$2,614	11.0

Of all envelope remediation options examined, air sealing of doors and window frames tend to be the most cost effective, with a typical payback period of 2.2 years for door frames and 3.2 years for window frames. The table above shows both estimated base-wide potential savings for identified components and the payback period for all measures considered.

A significant portion of envelope-related remediation savings comes from improving wall insulation. This is to be expected, as walls comprise the majority of the surface area of most buildings on the base. Wall insulation retrofits can be cost effective for the more emissive surfaces, and the thermal imaging data can help provide an essential pre-assessment to determine the surfaces to target for improvements. The total savings available at each different payback period may be examined by reviewing the cumulative savings across all measures by payback period (Figure 15).

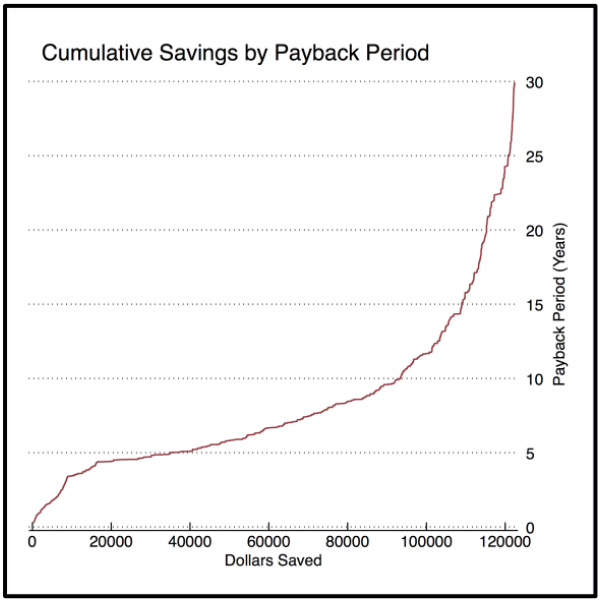

Figure 15. Cumulative annual energy cost savings by payback period, Scott AFB.

Calculated potential annual savings resulting from envelope-related remediation of imaged surfaces were $35,000 with a payback period of less than 5 years, over $93,000 in annual savings

with a payback of less than 10 years, and over $113,000 in annual savings with a payback of less than 15 years.

5.6.1.4 Portfolio Strategy Analysis for Camp Lejeune, NC

The Essess team also identified 2,883 distinct feature components on 147 different buildings on Camp Lejeune out of a total of 1,307 buildings and other objects surveyed. These features were categorized by type (e.g., brick wall, roof, window glass, window frame) and surface temperature. Heat losses were calculated based on the temperatures of the features, the times of observation, the orientations of the features, and the outdoor air temperatures.

Table 4 lists the potential savings and payback period for each category of envelope-related remediations for all imaged buildings at Camp Lejeune, NC.

Table 4. All recommended envelope-related remediations, Camp Lejeune.

Measure	Potential Savings	Payback Period
Seal Door Frame Leaks	$2,695	3.7
Seal Window Frame Leaks	$7,081	5.1
Basement Wall Insulation	$1,262	9.6
Improve Wall Insulation	$26,395	9.7
Improve Soffit Insulation	$952	10.7
Improve Roof Insulation	$598	14.0

Of all envelope remediation options examined, air sealing of doors and window frames tend to be the most cost effective, with a typical payback period of 3.7 years for door frames and 5.1 years for window frames. The table above shows both estimated base-wide potential savings for identified components and the payback period for all measures considered.

A significant portion of envelope-related remediation savings comes from improving wall insulation. This is to be expected, as walls comprise the majority of the surface area of most buildings on the base. Wall insulation retrofits can be cost effective for the more emissive surfaces, and the thermal imaging data can help provide an essential pre-assessment to determine the surfaces to target for improvements.

The total savings available at each different payback period may be examined by reviewing the cumulative savings across all measures by payback period (Figure 16).

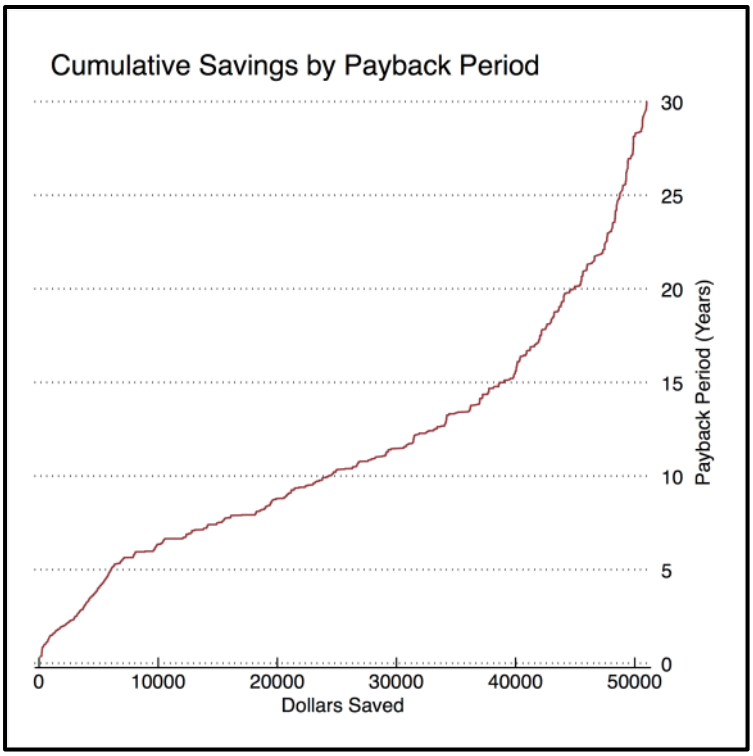

Figure 16. Cumulative annual energy cost savings by payback period, Camp Lejeune.

There are potential annual envelope-related remediation savings of approximately $6,000 from imaged surfaces with a payback period of less than 5 years, over $24,000 in annual savings with a payback of less than 10 years, and over $39,000 in annual savings with a payback of less than 15 years.

5.6.2 Building-by-Building Recommended Envelope ECMs

A number of building-envelope-related ECMs were recommended for specific buildings on each base. These were determined by a combination of thermal imaging, energy consumption analysis and disaggregation, and building characteristics. Recommended building envelope ECMs included: (1) improve wall insulation, (2) improve roof insulation, (3) improve soffit insulation, (4) improve exposed basement wall insulation, (5) seal window frame leaks, and (6) seal door frame leaks. Table 5 lists recommended building envelope ECMs for Scott AFB and Table 6 lists recommended building envelope ECMs for Camp Lejeune.

Table 5. Recommended building envelope ECMs for Scott AFB.

Bldg No.	Action	Material	Init R Value	New R Value	Savings ($)	Cost ($)	Payback (yrs)
1600	Improve Wall Insulation	Brick	8.1	13.7	2509	11427	4.6
533	Improve Wall Insulation	Brick	8.1	13.6	1835	8337	4.5
1600	Improve Wall Insulation	Brick	8.4	13.6	1733	8706	5.0
1575	Improve Wall Insulation	Brick	8.4	13.6	1511	7694	5.1
1575	Improve Wall Insulation	Brick	8.0	13.7	1436	6327	4.4
1575	Improve Wall Insulation	Brick	8.3	13.7	1382	6721	4.9
40	Improve Wall Insulation	Brick	8.9	13.6	1362	8041	5.9
533	Improve Wall Insulation	Brick	8.2	13.6	1338	6306	4.7
1989	Improve Wall Insulation	Brick	8.6	13.6	1043	5628	5.4
1456	Improve Wall Insulation	Siding	6.9	10.0	1022	5340	5.2
1600	Improve Wall Insulation	Brick	8.3	13.6	865	4195	4.8
56	Improve Wall Insulation	Brick	8.8	13.6	732	4257	5.8
61	Improve Wall Insulation	Brick	8.8	13.5	650	3804	5.9
1644	Improve Wall Insulation	Concrete	6.1	10.0	627	2264	3.6
1989	Improve Wall Insulation	Brick	8.7	13.5	622	3559	5.7
1989	Improve Wall Insulation	Brick	8.4	13.6	586	2975	5.1
3296	Improve Wall Insulation	Brick	8.1	13.7	555	2519	4.5
5000	Improve Wall Insulation	Brick	8.7	13.7	552	3070	5.6
5022	Seal Window Frame Leak	Roof	10.0	15.0	227	66	0.3
1989	Improve Roof Insulation	Soffit	8.4	13.7	227	1642	7.2
1575	Improve Soffit Insulation	D Frame	N/A	N/A	147	775	5.3
1650	Seal Door Frame Leak	W Frame	N/A	N/A	117	66	0.6
1530	Seal Window Frame Leak	Soffit	8.6	13.7	113	66	0.6
1987	Improve Soffit Insulation	W Frame	N/A	N/A	94	538	5.7
10	Seal Window Frame Leak	W Frame	N/A	N/A	82	66	0.8
8	Seal Door Frame Leak	D Frame	N/A	N/A	73	66	0.9
1650	Seal Door Frame Leak	D Frame	N/A	N/A	70	66	0.9
1600	Seal Window Frame Leak	W Frame	N/A	N/A	68	66	1.0
3189	Seal Door Frame Leak	D Frame	N/A	N/A	67	66	1.0
5000	Improve Soffit Insulation	Soffit	8.7	13.6	51	299	5.9

Table 6. Recommended building envelope ECMs for Camp Lejeune.

Bldg No.	Action	Material	Init R Value	New R Value	Savings ($)	Cost ($)	Payback (yrs)
2600	Improve Wall Insulation	Brick	8.5	13.6	1101	8727	7.9
895	Improve Wall Insulation	Brick	9.9	13.7	888	11929	13.4
HP210	Improve Wall Insulation	Brick	8.1	13.6	714	5094	7.1
8	Improve Wall Insulation	Brick	9.5	13.7	715	8219	11.5
1	Improve Wall Insulation	Brick	9.3	13.6	681	7345	10.8
401	Improve Wall Insulation	Brick	9.2	13.6	592	6155	10.4
1	Improve Wall Insulation	Brick	9.4	13.7	568	6272	11.1
HP104	Improve Wall Insulation	Brick	9.0	13.6	486	4568	9.4
62	Improve Wall Insulation	Brick	10.4	13.6	327	5542	16.9
407	Improve Wall Insulation	Brick	9.3	13.6	331	3480	10.5
20	Improve Wall Insulation	Brick	10.1	13.6	317	4756	15.0
1	Seal Door Frame Leaks	D Frame	N/A	N/A	76	65	0.8
1826	Improve Wall Insulation	Siding	8.4	10.0	518	11315	21.9
2905	Improve Wall Insulation	Siding	7.9	10.0	352	5211	14.8
2603	Improve Wall Insulation	Brick	9.7	13.6	360	4470	12.4
8	Improve Wall Insulation	Brick	10.5	13.6	262	4666	17.8
18	Improve Wall Insulation	Brick	10.8	13.7	244	4832	19.8
424	Improve Wall Insulation	Brick	8.3	13.6	243	1833	7.5
430	Improve Wall Insulation	Brick	9.6	13.5	240	2936	12.2
8	Improve Wall Insulation	Brick	9.6	13.6	242	2837	11.7
408	Improve Wall Insulation	Brick	9.4	13.6	214	2369	11.1
2917	Improve Wall Insulation	Siding	7.8	10.0	273	3762	13.8
2913	Improve Wall Insulation	Siding	7.9	10.0	388	5569	14.4
235	Improve Wall Insulation	Brick	8.5	13.6	229	1860	8.1
217	Improve Wall Insulation	Brick	10.3	13.7	211	3203	15.2
2903	Improve Wall Insulation	Siding	7.7	10.1	498	6119	12.3
2600	Improve Wall Insulation	Brick	9.8	13.7	257	3253	12.7
408	Improve Wall Insulation	Brick	10.1	13.7	184	2608	14.2
2600	Improve Soffit Insulation	Soffit	8.9	13.6	58	571	9.9
2613	Improve Roof Insulation	Roof	10.8	15.0	336	4942	14.7

5.6.3 Recommended Non-Envelope ECMs

Although not required by the project scope, Essess provided, at no additional cost to ESTCP, a rough estimate of about $928,330 of potential annual energy cost savings from non-envelope remediation measures at Scott AFB. This rough estimate of cost savings was arrived at by making assumptions about the buildings' occupancies, square footages, vintages, apparent condition of the buildings and the technologies that were assumed to be currently installed in the buildings. Based on these assumptions, Essess estimated a cost of $7,691,294 to upgrade the Scott AFB buildings with more energy efficient technologies for an estimated total payback of 8.3 years. These savings were assumed to come primarily through the replacement of existing T8 fluorescent lamps and ballasts with high performance T8 lamps and through the use of occupancy sensors to control lighting. The number of lighting fixtures and savings potential is estimated based on the square footage and types of building. Of the non-envelope measures, occupancy sensors and low flow showerheads (for residential buildings) had the lowest payback

period, at 1 and 1.7 years respectively. Table 7 lists all recommended non-envelope remediations for Scott AFB, IL.

Table 7. All recommended non-envelope remediations, Scott AFB.

Measure	Potential Savings	Payback Period
Occupancy Sensors	$254,396	1.0
Low Flow Showerheads	$1,213	1.7
Light Emitting Diode (LED) Exit Signs	$67,442	2.2
Compact Fluorescent Lamps (CFL)	$5,200	2.6
Programmable Thermostats	$3,724	2.7
Boiler Tune-ups	$8,028	4.0
EnergyStar Vending Machines	$10,446	4.3
Smartstrip Controls	$587	5.9
Fluorescent Lights	$567,294	12.6

As at Scott AFB, Essess provided a rough estimate of approximately $373,201 of potential annual energy cost savings at Camp Lejeune from non-envelope remediation measures. This rough estimate was based on assumptions about the buildings' occupancies, square footages, vintages, apparent conditions and the technologies that might be currently installed in the buildings. Based on these assumptions, Essess estimated a cost of $2,448,407 to upgrade these buildings with more energy efficient technologies for an estimated total payback of 6.6 years. These savings were assumed to come primarily through the replacement of existing T8 fluorescent lamps and ballasts with high performance T8 lamps and through the use of occupancy sensors to control lighting. The number of lighting fixtures and savings potential is estimated based on the square footage and types of building. Of the non-envelope measures at Camp Lejeune, occupancy sensors and low flow showerheads (for barracks facilities and fitness centers) have the lowest payback period, at 0.7 and 1.7 years respectively. Table 8 lists all recommended non-envelope remediations for Camp Lejeune, NC.

Table 8. All recommended non-envelope remediations, Camp Lejeune.

Measure	Potential Savings	Payback Period
Occupancy Sensors	$105,440	0.7
Low Flow Showerhead	$552	1.7
LED Exit Signs	$30,874	2.2
Replace Incandescent Bulbs with CFLs	$943	2.6
Smartstrips	$267	5.9
Efficient Fluorescent Lights	$235,126	9.8

It should be noted that no effort was made by Essess to perform a walk-through audit of either the Scott AFB or Camp Lejeune facilities. The relative paucity of building-specific information prevents a more detailed assessment of non-envelope savings options. Identification and validation of the expected energy cost savings and the cost of implementation of specific non-envelope ECMs would require further investigation through other energy auditing techniques.

6.0 PERFORMANCE ASSESSMENT

The KSR LWIR approach provided a number of significant advantages over conventional handheld IR thermography in terms of the speed and cost of imaging and the quality and utility of the images and analysis. Images were acquired at a much faster rate using the Essess sensor system. There was continuous thermal image acquisition without the need to manually frame the buildings since each video frame contained overlapping information. Further, the raw information gathered in the continuous thermal image acquisition allowed temperature conversions to be performed per individual region in the frames, a significant improvement over the handheld thermography process, which converts only one temperature point. The Essess system also provided NIR images associated with each LWIR image. These provided the ability to pick out features and textures that might not have been easily visible in the LWIR image, as the NIR images are similar in appearance to a conventional grayscale photograph.

Results of a one-to-one comparison of handheld imaging with the vehicle scanning system made it clear that the mobile imaging system can collect thermal imaging data in a far more scalable and efficient manner than can traditional handheld thermography. Furthermore, the Essess imaging rig is equipped with multiple sensors including NIR cameras and LIDAR, which, when combined with KSR LWIR, allows significantly more information gathering than would be possible using traditional thermography. This includes building façade data and building orientation. The automated data processing system also allows an efficient and accurate analysis of each image, which contributes to detailed, accurate reporting. This type of quantitative analysis is not possible using the handheld system as it is impossible to accurately quantify how much energy is leaking out of one area of a building versus another area. In terms of speed, resolution, and FOV, Essess' scanning system exceeded the handheld unit by a significant margin.

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7.0 COST ASSESSMENT

The total cost for scanning, analyzing and producing a report for Camp Lejeune and Scott AFB was $404,577. For the purposes of this demonstration both installations were treated as a single project and the costs were broken up by phases rather than a per-building cost.

7.1 COST MODEL

For all three phases, the majority of the costs were for direct labor and contracting Subject Matter Experts for computer vision aided data processing using commercial thermography and energy modeling. Phase 1 costs were related to the customization of the imaging hardware and creating logistics software for the driving team to navigate while imaging. To capture data in the most efficient manner, the driving team was guided by an onboard navigation system with route guidance based on the installations' street networks. This had to be created for each base, as complete road network information for these military installations was unavailable. For Camp Lejeune and Scott AFB the total Phase 1 costs were $103,721.

Phase 2 costs were related to data capture and analysis. Essess drove the imaging vehicle to Camp Lejeune and Scott AFB and captured thermal, NIR, LIDAR, and GPS data. Once the data were sent to Essess headquarters, they were processed (the raw data were converted into temperature images and the temperature images were correlated to the correct GPS coordinates based on vehicle GPS and military provided GIS information). After the data were processed, the second part of Phase 2 analyzed the processed data to detect building thermal inefficiencies and leaks in the building envelope. The Contractor also built an online Drive-by Application to enable Facility Engineers at Camp Lejeune and at Scott AFB to down select buildings for further analysis. The total cost for Phase 2 was $168,032.

Phase 3 consisted of aggregating the mobile thermal imaging results, analyzing the handheld thermography data, and preparing a Final Report. The total cost for Phase 3 was $106,356.

Table 9 lists "model" costs for a single military installation. Essess has the capability to image hundreds of bases in a single winter while maintaining the same cost structure making the technology extremely scalable.

Table 9. Cost model for imaging a military installation.

Cost Element (for Single Military Installation)	Estimated Costs
Phase 1: Hardware Customization and Logistics Software Optimization	$51,861
Phase 2: Data Capture, processing and Analysis	$81,567
Phase 3: Aggregating analyzed data in a report format	$50,744

7.2 COST DRIVERS

There are no major cost drivers for this technology as it is applicable to military bases across various ASHRAE Climate Zones. The technology is efficient and scalable, which allows Essess to image bases significantly larger than Scott AFB without increasing the cost structure. Unlike a

typical auditor that charges per building, Essess' cost structure is on a per installation basis, due to the fact that the bulk of Essess' costs are front-loaded. Once the imaging rig is deployed to an installation, the cost difference between imaging 100 buildings versus 1,000 buildings is marginal.

7.3 COST ANALYSIS AND COMPARISON

The operational implementation of the technology requires significant customization to the hardware rig and to the logistics, processing and analysis software. As a result, Essess' thermal imaging, data processing, data analysis and reporting costs are roughly $200,000 per military installation.

Traditionally, the only way to obtain envelope efficiency information was to use a handheld thermal camera to capture IR thermal images building-by-building. As a result, handheld thermography is relatively labor intensive and requires a human to interpret each image. Essess' drive-by method has the ability to quickly capture thermal imagery for hundreds of buildings and automatically analyze thousands of thermal images. Furthermore, commercial energy audits that include envelope thermal imaging using handheld thermography typically cost around $0.20/sq ft of building area (based on data from local thermal imaging auditors within 100 miles of Scott AFB and Green-Buildings.com). Essess imaged, processed and analyzed data and developed reports for 4.6 million sq ft of building space at Scott AFB and 4.2 million sq ft at Camp Lejeune for $404,577. Based on the costs noted above, having the same amount of building space analyzed with a handheld camera would have cost approximately $1,760,000 ($920,000 for Scott AFB and $840,000 for Camp Lejeune). That is $1,355,423 more than Essess' mobile imaging costs.

8.0 IMPLEMENTATION ISSUES

This technology is limited to scanning the street sides of buildings. As a result, for most buildings, four sides of the buildings will not be scanned. Two or three sides can often be scanned depending on the orientation of a building relative to the street. This technology is also limited by the requirement to have a ΔT between building interior and exterior ambient temperatures of at least 20°F, so scanning must occur when nighttime temperatures are below 50°F. This limits application of this technology to regions where there is at least 1 week of the year in which nighttime temperatures are below 50°F. Most regions of the United States fall within this boundary condition. Adjustments are made for empty buildings or buildings where there is no internal heating and no way of knowing the internal temperature setpoint. This technology is somewhat hindered by trees, bushes and other obstructions that might partially obscure a clear view of a building's envelope from the street. However, the automated data processing pipeline developed by Essess to take the scanned data and prepare it for a report format corrects for these kinds of obstructions in a number of ways that have been tested and validated by Essess.

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APPENDIX A

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