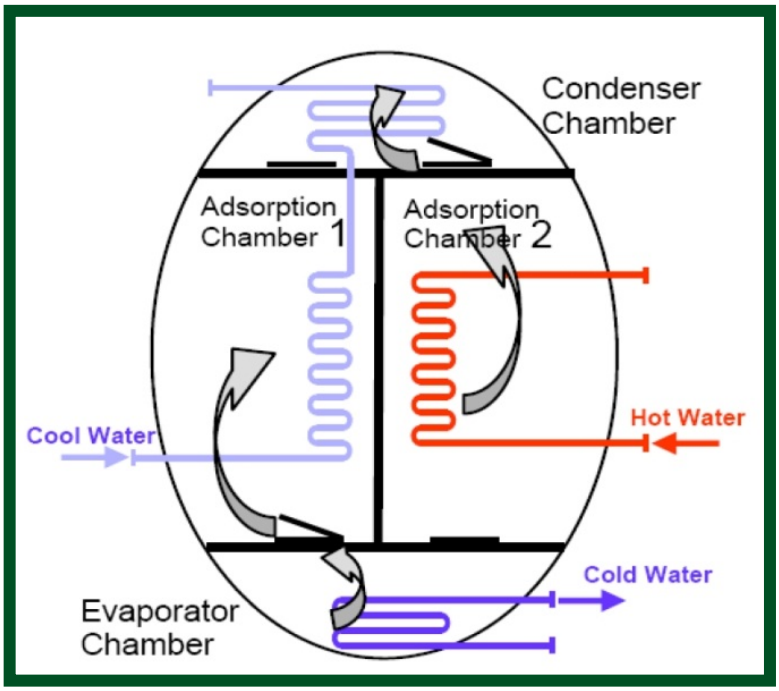
ESTCP
Cost and Performance Report

(EW-200928)



Demonstration of a Solar Thermal Combined Heating, Cooling and Hot Water System Utilizing an Adsorption Chiller for DoD Installations

March 2014

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ESTCP

ENVIRONMENTAL SECURITY
TECHNOLOGY CERTIFICATION PROGRAM

U.S. Department of Defense

COST & PERFORMANCE REPORT
Project: EW-200928

TABLE OF CONTENTS

		Page
EXECUTIVE SUMMARY		ES-1
1.0	INTRODUCTION	1
1.1	BACKGROUND	1
1.2	OBJECTIVE OF THE DEMONSTRATION	2
1.3	REGULATORY DRIVERS	2
2.0	TECHNOLOGY DESCRIPTION	3
2.1	TECHNOLOGY OVERVIEW	3
2.1.1	Adsorption Chiller	3
2.1.2	Evacuated Tube Solar Panels	3
2.1.3	Applications within DoD	4
2.1.4	Technology Development	4
2.2	ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY	4
2.2.1	Adsorption Chiller Advantages and Limitations	4
2.2.2	Solar Collector Array Advantages and Limitations	5
3.0	PERFORMANCE OBJECTIVES	7
4.0	FACILITY/SITE DESCRIPTION	9
4.1	FACILITY LOCATION AND OPERATIONS	9
4.2	FACILITY CONDITIONS	9
5.0	TEST DESIGN	13
5.1	CONCEPTUAL TEST DESIGN	13
5.2	BASELINE CHARACTERIZATION	13
5.3	DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS	14
5.4	FACTORY ACCEPTANCE TEST	15
5.5	OPERATIONAL TESTING	16
5.6	SAMPLING PROTOCOL	17
5.7	SAMPLING RESULTS	18
6.0	PERFORMANCE ASSESSMENT	19
6.1	SUMMARY OF PERFORMANCE OBJECTIVES AND RESULTS	19
6.2	PERFORMANCE RESULTS FOR DEMONSTRATION PLAN OBJECTIVES	19
6.2.1	Peak Cooling Capacity	20
6.2.2	Maximum Cooling Capacity Driven by Solar Energy Alone	20
6.2.3	Steam Energy Reduction	20
6.2.3.1	Domestic Hot Water	21
6.2.3.2	Parasitic Loads	21
6.2.4	GHG Emission Footprint Reduction	22
6.2.5	Availability and Reliability	22
6.2.6	Economic Performance	23

TABLE OF CONTENTS (continued)

Page

6.2.7 Operability/Ease of Use 23

7.0 COST ASSESSMENT 25
7.1 COST MODEL 25
7.1.1 Capital Costs 25
7.1.2 Operation and Maintenance Savings 26
7.1.3 Service Life 26
7.2 COST DRIVERS 26
7.3 COST ANALYSIS 27
7.3.1 Parris Island Installation 27
7.3.2 Differential Cost Analysis 28
7.3.3 Alternative Performance Scenarios 29
7.4 COST COMPARISONS 30

8.0 IMPLEMENTATION ISSUES 31

9.0 REFERENCES 33

APPENDIX A POINTS OF CONTACT A-1

LIST OF FIGURES

Page

Figure 1. Location of Building 590 and Central Steam Plant. 9

LIST OF TABLES

Page

Table ES-1. Performance objectives and outcomes. ES-2
Table 1. Operational summary. 16
Table 2. Performance objectives and results. 19
Table 3. Incremental operation and maintenance savings. 26
Table 4. Economic projections for alternate performance scenarios. 29

ACRONYMS AND ABBREVIATIONS

AHU	air handler unit
ASHRAE	American Society of Heating Refrigeration and Air-conditioning Engineers
BLCC	Building Lifecycle Cost
BMS	building management system
BoP	Balance of Plant
BTU/hr	British thermal units per hour
CO_2e	carbon dioxide equivalent
COP	coefficient of performance
DHW	domestic hot water
DoD	U.S. Department of Defense
ECAM	Environmental Cost Analysis Methodology
EIA	Energy Information Administration
ESTCP	Environmental Security Technology Certification Program
EU	European Union
EF	degrees Fahrenheit
FAT	Factory Acceptance Test
FMD	Facilities Maintenance Division
FY	fiscal year
GHG	greenhouse gas
HCFC	hydrochlorofluorocarbon
HFC	hydrofluorocarbon
HP	horsepower
HVAC	heating, ventilation and air conditioning
kW	kilo Watt
mA	milliamp
MMBtu	million British thermal units
N/A	Not applicable or not available
NPV	net present value
O&M	operation and maintenance
PIFMD	Parris Island Facilities Management Division
PIMCRD	Parris Island Marine Corps Recruit Depot
psi	pounds per square inch

ACRONYMS AND ABBREVIATIONS (continued)

PV	photo voltaic
QAiST	Quality Assurance in Solar Heating and Cooling Technology
RT	Tons refrigeration (cooling energy units)
SRI	Southern Research Institute
SUT	System Under Test
U.S.	United States
VFD	variable frequency drive

ACKNOWLEDGEMENTS

This project is funded under the U.S. Department of Defense Environmental Security Technology Certification Program (ESTCP), Sustainable Infrastructure Program. This report was developed by Southern Research Institute in accordance with the requirements of this program.

We would like to acknowledge the following organizations, programs, and individuals for the valuable contribution to this document.

Parris Island Marine Corps Recruit Depot:

- Lieutenant Colonel Miller, Facilities Maintenance Officer
- Richard Pierce, Energy Manager (Project champion and Point of Contact [POC])
- Dr. Herman Brown, Resource Efficiency Manager, (contractor)
- Lieutenant Commander Rob Zhang, Public Works Officer
- Roy McAlhany, Planner and Estimator (Heating, Ventilation and Air Conditioning [HVAC]/Electrical Engineering Technician)
- Ronnie Myers, Deputy Facilities Maintenance Officer (Second POC)

Vanir Energy

- Steve Hunter
- Steve Toy
- Don Haase

Power Partners

- Tom Lopp
- Wes Livingston
- Phillip Sullivan

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EXECUTIVE SUMMARY

OBJECTIVES OF THE DEMONSTRATION

Technologies used to provide cooling for buildings at U.S. Department of Defense (DoD) sites represent a substantial portion of the energy consumption at fixed installations and forward operating bases. Conventional vapor compression and absorption cooling systems involve refrigerants and chemicals that require special handling to prevent toxic exposure or harmful discharge into the environment. With increasing energy costs, the economic and security impacts of cooling loads are an important consideration when planning for retrofit improvements and new installations.

The objective of this project was to demonstrate the technical and economic efficacy of a solar-thermal cooling system using an adsorption chiller at the Parris Island Marine Corps Recruit Depot (PIMCRD) in South Carolina. Quantitative and qualitative performance objectives included demonstrating:

- Peak cooling capacity;
- Maximum capacity using solar energy alone;
- Steam and electrical energy reductions and associated emissions footprint reductions;
- Operability and reliability; and
- Economic benefits.

TECHNOLOGY DESCRIPTION

The primary components of the demonstrated technology are an adsorption chiller, an array of evacuated tube solar panels, and balance of plant equipment (e.g., pumps and piping) necessary to support operation of the system as integrated with existing heating, ventilation and air conditioning (HVAC) equipment at the site (e.g., air handlers and controls). The system design also included the ability to utilize excess solar thermal energy (e.g., in winter months) for domestic water heating.

Adsorption chillers are better suited than absorption chillers for solar thermal applications due to their ability to operate over a wider range of hot water supply temperatures (as low as 120 degrees Fahrenheit [°F]). Adsorption chillers, like all chillers, extract heat from the environment by way of vaporization of a refrigerant liquid. In an adsorption chiller, the refrigerant (water) is evaporated under vacuum conditions. It is then adsorbed (condensed) onto a solid sorbent; in this case, silica gel. The silica gel is regenerated (desorbed) using hot water supplied by solar energy and/or steam.

Evacuated tube solar panels were employed due to their higher efficiency and higher output temperatures compared to flat panel collectors.

The demonstration was conducted at the 1st Battalion Mess Hall (Building 590) located at PIMCRD. The baseline cooling system was an absorption chiller (90 tons refrigeration [RT])

powered by steam for cooling the dining area. An electric chiller (60 RT) was used to cool the kitchen area.

The conceptual test design was to evaluate the performance of the existing system before modification as a baseline and compare this to the performance of the modified system to determine energy savings. In addition, the performance of major sub-components of the system was to be evaluated. Major sub-components included the adsorption chiller, the solar array loop, and the domestic hot water (DHW) system.

DEMONSTRATION RESULTS

Table ES-1 summarizes the demonstration plan performance objectives, success criteria and demonstration results. None of the demonstration objectives were fully satisfied. Although operation of the adsorption chiller was not demonstrated at full rated capacity, analysis shows that this limitation resulted from balance of plant design and implementation issues, not inherent problems with the adsorption chiller. The solar array performed exactly as expected. Due to construction delays, system design, and site integration issues, the DHW system was not operational prior to the end of the demonstration. Additional details that impacted demonstration results are discussed in the following section on implementation issues.

Table ES-1. Performance objectives and outcomes.

Performance Objective	Success Criteria	Results
Quantitative Performance Objectives		
Determine peak cooling capacity of the SUT	Peak cooling capacity of SUT must be greater than 80 RT	Objective not met. Maximum sustained cooling was 52.8 RT.
Determine max cooling capacity of the SUT when driven by solar energy only	When DHW solar energy demand is zero, peak cooling capacity of SUT must be greater than 60 RT without supplemental steam	Objective could not be evaluated. The final system design did not permit the system to be operated on solar output alone.
Steam energy reduction	Steam energy reduction will exceed 800 MMBtu/year including cooling and DHW	Objective not met. Annualized net steam energy reduction over baseline was 703.8 MMBtu/year.
Emission foot print reduction	Reductions exceed: 79 metric tons CO_2e per year relative to baseline.	Objective not met. Net GHG emissions reduction was 32.1 metric tons CO_2e per year.
Equipment availability and reliability	>99% availability. >99% reliability.	Objective not met. Overall system availability and reliability could not be quantitatively assessed due to ongoing operational issues throughout the demonstration.
Assess economic performance	Simple payback < 7 years; Positive NPV based on ECAM and BLCC	Objective not met. Site-specific payback will not be achieved within the system lifetime.

BLCC = Building Lifecycle Cost
CO_{2e} = carbon dioxide equivalent
ECAM = Environmental Cost Analysis
GHG = greenhouse gas
MMBtu = million British thermal units
NPV = net present value

Table ES-1. Performance objectives and outcomes (continued).

Performance Objective	Success Criteria	Results
Qualitative Performance Objectives		
Determine Ease of use	The average points above neutral (or above three points)	Objective could not be fully evaluated as the system did not achieve stable, routine operations during the demonstration period. The system is complex and unfamiliar. Training and documentation were incomplete as of the end of the demonstration. Implementation issues complicated operations.

IMPLEMENTATION ISSUES

Unexpected technical and management issues were encountered during the course of the project that negatively impacted the outcome of the demonstration. Significant issues included:

- The available roof area was insufficient to support the planned solar thermal capacity.
- The initial design for chiller operation on solar or steam energy alone was unworkable due to insufficient solar capacity to operate the chiller on solar energy alone as well as piping design issues that prevented operation on steam without utilizing the solar buffer tank.
- The piping design failed to account for normal water transfer between the hot water and tower loops within the chiller.
- The solar field piping construction, though built to manufacturer specifications, was inadequate to withstand high temperatures during stagnation events.
- The initial piping design had inadequate provision for pressure relief and release of entrapped air.
- The initial control sequence was incomplete, which caused delays in system commissioning.
- The design failed to make adequate provisions to ensure that chiller supply flows and temperatures would meet the chiller submittal specifications.

In Southern's opinion, the original design was incomplete and inadequate. Southern's technology partner, Vanir Energy, was not fully responsive to the requirements of a demonstration project, resulting in delays in addressing design and operability issues as they arose. As a result, Southern was unable to optimize or fully evaluate all aspects of system performance before the end of the demonstration period.

The adsorption chiller factory acceptance test conditions matrix did not anticipate the range of possible supply flow and temperatures to the chiller that might be encountered in the field, or span the range of chiller cycle timing that might be employed to optimize performance under

field conditions. This inadequate testing made it impossible to quantitatively determine whether the chiller performance in the field was within the expected range, and complicated efforts to optimize chiller performance in the field.

There were also issues with building HVAC systems maintenance that negatively impacted Southern's ability to fully evaluate the performance of the test system. In particular, during much of the 2012 cooling season, maintenance issues with the electric chiller (installed in series with the adsorption chiller) affected adsorption chiller performance such that results were not representative of normal chiller performance.

Based on Southern's experience with this demonstration and findings from other researchers (Dickinson, et al., 2010; Ishaya, 2011) , the capital cost of a solar thermal chiller system using evacuated tube collectors is unlikely to be recovered from energy savings alone. A thorough design effort accounting for net parasitic loads, piping friction head, and building HVAC system operating details would be required to achieve payback within the system lifetime (20-30 years).

1.0 INTRODUCTION

This project demonstrated the technical and economic efficacy of a solar-thermal cooling and heating system using an adsorption chiller deployed at Parris Island Marine Corps Recruit Depot (PIMCRD). Solar energy was collected using an array of 85 evacuated tube solar panels each with a total effective aperture area of 4131 square feet. The resulting hot water was used to drive an adsorption chiller rated to provide 80 tons refrigeration (RT) of comfort cooling to the host facility. Energy not required for cooling may be used to heat domestic hot water (DHW).

1.1 BACKGROUND

Present technologies used to provide heating and cooling for buildings at U.S. Department of Defense (DoD) sites represent a substantial portion of the energy consumption at fixed installations and forward operating bases. A combination of electric power and steam energy is used, often from coal or hydrocarbon combustion. Conventional mechanical and absorption cooling systems involve refrigerants and chemicals that require special handling to prevent discharge into the environment. With increasing energy costs, the economic and security impacts of heating and cooling loads are an increasingly important consideration when planning for retrofits and future installations.

The adsorption chiller demonstrated for this project replaced an aging absorption chiller operated on steam. The adsorption chiller uses municipal quality water as the refrigerant. The water is cyclically adsorbed and desorbed from a silica gel desiccant. Both the desiccant and the refrigerant are environmentally benign. The adsorption chiller is capable of utilizing low grade (> 120 degrees Fahrenheit [°F]) solar thermal or waste heat sources; operating over a wide range of thermal input and heat removal conditions; and has very low maintenance and power requirements.

Thermally driven absorption chillers are well proven; however, they depend on the use of toxic or corrosive refrigerant solutions (typically lithium bromide); require more tightly controlled thermal input and heat removal conditions; and have significant maintenance and power requirements. Compared to mechanical chillers, adsorption chillers have lower maintenance, lower operating costs, lower noise, and do not require hydrofluorocarbon (HFC) refrigerants. HFC refrigerants are relatively costly and require special handling to avoid atmospheric release due to their high global warming potential.

Benefits of the solar thermal cooling and DHW heating system include:

- Reducing energy consumption and exposure to energy price volatility;
- Reducing electricity and boiler associated emissions of criteria pollutants and greenhouse gases;
- Reducing life-cycle environmental impacts of cooling equipment by using water as the refrigerant; and
- Reducing dependence on petroleum-based fuels providing enhanced security.

1.2 OBJECTIVE OF THE DEMONSTRATION

The objective of this project was to demonstrate the technical and economic efficacy of a solar-thermal heating and cooling system using an adsorption chiller at the PIMCRD in South Carolina. Quantitative and qualitative performance objectives are presented in section 6.1 and include demonstrating:

- Peak cooling capacity,
- Maximum capacity using solar energy alone,
- Steam and electrical energy reductions and associated emissions footprint reductions
- Operability and reliability, and
- Economic benefits.

1.3 REGULATORY DRIVERS

Energy security, environmental sustainability, improved reliability and long-term savings are all drivers for the subject technology. On October 5, 2009, President Obama issued Executive Order 13514 titled "Federal Leadership in Environmental, Energy and Economic Performance." This Order challenges all federal agencies to establish greenhouse gas emissions reduction targets, specifically "reducing energy intensity in agency buildings," and "increasing agency use of renewable energy…" The order goes on to require plans that will, among other things, "decrease agency use of chemicals where such decrease will assist the agency in achieving greenhouse gas emission reduction targets…" The Order also requires that beginning in 2020, all new buildings commencing planning will be "designed to achieve zero net energy by 2030" and "pursuing cost-effective, innovative strategies to minimize consumption of energy, water and materials."

Executive Order 13423, titled "Strengthening Federal Environmental, Energy, and Transportation Management," includes the following goals: Energy efficiency improvements and greenhouse gas emissions reductions by way of reduction in energy intensity by 1) 3% annually through fiscal year (FY) 2015, or 2) 30% by FY 2015, relative to FY03 baseline, and 3) 50% of statutorily required renewable energy consumed has to come from new renewable sources.

Finally, the Defense Authorization Act FY2007, SEC. 2852, focuses on renewable energy application for electricity needs, referencing the Energy Policy Act of 2005. Although not directly applicable, in some applications, the proposed technology may offset grid electricity usage via implementation of a renewable energy technology and energy efficiency measures.

2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY OVERVIEW

The primary components of the demonstrated technology are 1) an adsorption chiller, and 2) an array of evacuated tube solar panels. Each of these components is described below, followed by a brief discussion of possible DoD applications.

2.1.1 Adsorption Chiller

Vanir Energy (formerly Appalachian Energy) selected the Eco-Max adsorption chiller manufactured by Power Partners, Inc. of Athens, GA, for the demonstration. Vanir Energy purchased Appalachian Energy shortly after the demonstration began, but before construction commenced.

The Eco-Max chiller is based on technology created by Nishiyodo of Japan, with consultation from their engineering team and suppliers. Nishiyodo was the developer of the first commercial application of the technology. Chillers were a small but growing division of the company when Nishiyodo was forced to close its primary manufacturing business.

PowerPartners continues to manufacture the Eco-Max chiller in capacities ranging from 3-330 tons using silica gel or 250-450 tons using zeolite desiccant. Adsorption chillers are also currently manufactured by:

- Mayekawa (20-100 tons using zeolite desiccant),
- Union (10-125 tons using silica gel),
- Sortech - 2 ton units for residential use, and
- InvenSor - 3 ton units for residential use

Several other companies (GBU, AAA Machine, Mitsubishi AQSOA, Weatherite) claim to produce adsorption chiller units, but in fact rebrand units from one of the companies listed above.

Adsorption chillers, like all chillers, extract heat from the environment by way of vaporization of a refrigerant liquid. In a closed system, the liquid must then be re-condensed in some manner. In an adsorption chiller, the refrigerant (water) is evaporated under vacuum conditions. It is then adsorbed (condensed) onto a solid surface: silica gel.

2.1.2 Evacuated Tube Solar Panels

Vanir Energy (Southern's partner on this demonstration) selected Paradigma evacuated tube solar collectors manufactured by Ritter. The evacuated tube collectors have lower thermal losses than conventional glazed panels. The circular absorbing surfaces combined with an integrated reflector optimize energy yield at varying solar angles throughout the day and effectively capture diffuse as well as direct solar radiation. The tubes are resistant to hail impact and are easily replaced individually if damage occurs.

The solar panel array installed at Building 590 was designed by the manufacturer (Ritter) to operate in a closed loop. When there is no solar thermal demand, the water in the panels will flash to steam. Such an occurrence is called 'stagnation' of the array. During stagnation, high pressures and temperatures in excess of 350 °F may be generated. Expansion tanks are provided to take up the increased volume. Following stagnation, no further heat may be recovered from the solar array until the panels cool down (generally overnight).

2.1.3 Applications within DoD

According to a database of DoD real estate, DoD operates approximately 189,000 buildings in southern states with ~1283 million square foot area. Approximately 1% of the square footage was in buildings of 60,000 square feet (corresponding to 60 RT chiller) or greater. This means that there are about 214 potential applications in the southern United States (U.S.) (some of these will be larger capacity units resulting in fewer total units, i.e., a 125 RT unit would displace ~ 2x60 RT.) Mess halls normally have much higher cooling load/square foot than the average. As a result, the potential applications may be higher. Assuming a 20% penetration into this market, there could be as many as 43 installations at DoD facilities. The most common installations involve chillers of either 15-40 RT or 100-150 RT capacity.

2.1.4 Technology Development

No technology development work was conducted prior to the field demonstration as part of this ESTCP project. Silica-gel adsorption chilling was first commercially applied in 1986 by Nishiyodo. PowerPartners began manufacturing adsorption chillers in the United States in 2008. In the U.S., there are about 15 adsorption chillers currently installed. Worldwide, there are about 250 commercial units installed primarily in Japan, and approximately 100 residential units, installed mostly in Germany.

2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The following sub-sections present advantages and limitations of the major technology sub-components: the adsorption chiller and the evacuated tube solar collector panels.

2.2.1 Adsorption Chiller Advantages and Limitations

Alternatives to heat driven adsorption chillers include absorption chillers (also heat driven) and mechanical chillers (compressor driven).

Adsorption versus Absorption chillers

In general, the capital cost of equipment and balance of plant is higher for adsorption than absorption chillers. The efficiency (coefficient of performance [COP]) of absorption versus adsorption chillers is similar for similarly designed chillers, but tends to be somewhat higher for absorption chillers. PowerPartners has specified an adsorption chiller COP of 0.62 for loads exceeding 60 RT. The COP for absorption chillers typically falls in the range of 0.65 to 0.7.

Compared to typical absorption chillers using lithium bromide solution as absorbent, the EcoMax adsorption chillers have the following advantages:

- The silica gel adsorbent in the EcoMax chiller is non-toxic and the initial charge should last for the lifetime of the equipment. The lithium bromide charge in an absorption chiller typically needs to be replaced every 4-5 years. Lithium bromide is corrosive, increasing component replacement frequency, maintenance requirements, and shortening equipment lifetime relative to absorption chillers. Lithium bromide can crystallize within the system if operating conditions are not maintained within relatively tight tolerances. Lithium bromide is a hazardous material that requires special handling during maintenance and decommissioning.
- The EcoMax adsorption chiller can operate over a wide range of hot water supply temperatures (122 EF to 205 EF+). Absorption chillers typically require hot water supply temperatures in excess of 180 EF and hot water supply temperatures must be maintained within a fairly narrow band to prevent crystallization.
- Power requirements for the EcoMax adsorption chiller (excluding BoP) are very low (<0.5 kilo Watts [kW]). The absorption chiller that was replaced at the demonstration site consumed 5 kW.

Adsorption versus Mechanical Chillers

Mechanical chillers cannot make use of low grade thermal energy such as solar or waste heat; however, the efficiency for a mechanical chiller is much higher than for an adsorption or absorption chiller. For the same tonnage rating, a mechanical chiller will have a much smaller footprint and much lower weight. Noise and vibration levels are higher for mechanical chillers. The HFC or HCFC refrigerants used in mechanical chillers require special handling by certified technicians.

2.2.2 Solar Collector Array Advantages and Limitations

Solar thermal collector panels can effectively collect solar energy at minimal operating cost for the pump circulating the heat transfer fluid. The heat transfer fluid temperature can be high enough for the adsorption chiller to operate.

The main disadvantage of the solar heat collector is that it cannot provide energy if sunlight is not available. For most projects, a supplemental heat source is required. Another disadvantage of the solar system is the extent of the collector surface needed to capture the required energy. Many buildings may not have sufficient, unobstructed roof area available to mount the solar panels and many buildings may not have the correct, unobstructed orientation to the path of the sun for solar collectors to operate effectively.

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3.0 PERFORMANCE OBJECTIVES

The performance results for each demonstration plan objective are summarized in the executive summary of this cost and performance report. Section 6.0 of this report provides a more detailed discussion for each result. A complete presentation of the results and all issues encountered is provided in the final report.

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4.0 FACILITY/SITE DESCRIPTION

The facility selected for the demonstration was the First Battalion Mess Hall (Building 590) at the Parris Island Facilities Management Division (PIMCRD), SC. The site was selected over other suitable sites due to responsiveness and interest of the Parris Island energy manager and Facilities Maintenance Division (FMD) management and staff. A map showing the location of Building 590 is shown in Figure 1.

Figure 1. Location of Building 590 and Central Steam Plant.

4.1 FACILITY LOCATION AND OPERATIONS

The First Battalion Mess Hall serves 700 persons per seating, three seatings per meal, and three meals (breakfast, lunch, and dinner) per day, seven days per week. As a result, the live load (cooling load due to occupancy) is significant and fairly consistent each day. The amount of hot water used for preparing meals and washing dishes is also relatively consistent each day averaging about 8100 gallons per day with a typical range from 6000 to 10,000 gallons per day.

4.2 FACILITY CONDITIONS

Prior to the demonstration, the dining area of the 1st Battalion Mess Hall was cooled by a steam driven absorption chiller (Trane model ABSC-01B). This chiller was nominally rated at 112 RT capacity but was de-rated to 90 tons. The chiller was 12-15 years old at the time of replacement and was reportedly nearing the end of its useful life. The existing absorption chiller served an air handler unit (AHU) (AHU-1B) rated at 87.5 RT to provide cooling for the dining area, which comprises about 10,500 square feet.

In the pre-demonstration configuration, the kitchen and scullery (dish washing area) areas were cooled by an air cooled electric chiller rated at 60 RT. The kitchen area was served by an air handler (AHU-1A) rated at 43 RT. The scullery area was served by an air handler (AHU-2A) rated at 5 RT. The kitchen and scullery areas, together, comprise about 5200 square feet, excluding refrigerator and freezer space, and a dry storage area that is independently cooled.

The steam plant is located about one mile from Building 590 and runs primarily on natural gas with fuel oil backup. The location of the steam plant is shown in Figure 1 above. Steam is supplied to Building 590 via a base-wide above-ground steam distribution system. The steam supply pressure at Building 590 is regulated to 15 pounds per square inch (psi).

The cooling set-point temperature for the building is 78 EF. The traditional roof was replaced with a reflective "cool roof" in October 2009. Hot water for the kitchens and scullery is currently provided via steam converters. Comfort heat is provided by direct steam coils in the air handling units.

The existing heating, ventilation and air conditioning (HVAC) air handlers, piping and cooling tower were deemed by Vanir to be suitable for conversion to the new solar driven adsorption technology. This pre-existing equipment was left in place and continues to serve. The building was inspected by the system contractor (Vanir) and satisfactory sun-path orientation and unobstructed area of Building 590 for solar collection was confirmed.

In order to conduct a fair and unbiased demonstration, baseline and extended testing were planned to be conducted with the building HVAC systems in 'as found' condition – with the implicit assumption that the HVAC system was generally functioning and in a reasonable state of repair. As such, Southern made no attempt to assess the condition of building HVAC system prior to baseline testing. However, during baseline testing, it became apparent that a number of building HVAC components were not fully functioning.

Southern felt that in order to be able to properly assess the performance of the new solar chiller system, the condition of the building HVAC system should be known and in a reasonable state of repair. On February 1, 2011, Southern met on site with PIFMD's HVAC contractor to assess the condition of the existing HVAC system. A large number of problems were found and some of these were addressed over the following months as construction of the solar chiller system commenced. In short, the condition of the existing HVAC system was such that the building cooling load was much higher than it should have been. A record of findings and recommendations from this survey is on file (CTS Inc., 2011).

In August 2012, an engineer from PowerPartners conducted an additional survey of the building HVAC system, maintenance practices, and environmental controls. The conclusion of this survey was also that the building heat and humidity loads were much higher than necessary and recommendations were provided to reduce the cooling load (PowerPartners, 2012).

In another instance, Southern noted that the facility building management system (BMS) data showed that the fresh air damper for the main dining air handler was closed when, in fact, it was open: substantially increasing the building cooling load. Southern also noted discrepancies

between BMS temperature sensor values used to control the solar chiller system and Southern's independent sensors. Southern was unable to coordinate with PIFMD to assess the impact of these discrepancies on system control. Despite significant efforts to understand and address Building 590 HVAC issues, Southern was unable to fully characterize Building 590 HVAC system performance.

Southern's conclusion is that conditions at Building 590 may not be representative of typical HVAC system performance at other sites. This conclusion does not substantially impact the ability to evaluate of the performance of the solar chiller system in isolation, but did have an effect on the evaluation strategy as presented in the demonstration plan. Specifically, Southern was forced to conclude that comparison of system performance with baseline conditions using the strategy presented in the demonstration plan would not be representative and a new approach to evaluate energy savings based on direct measurements of solar energy input the system was adopted.

The condition of the HVAC system at Building 590 also has an impact on the perceived acceptability of the system to the building occupants and PIFMD. If the building remains uncomfortable, the new system may be perceived as inadequate. In addition, the energy savings gained by installation of the solar chiller system might have been more easily realized by proper maintenance and repair of existing system as well as modifications to building usage practices as outlined in the PowerPartners report.

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5.0 TEST DESIGN

The test design as set forth in the demonstration plan evolved during the conduct of the demonstration in response to system design changes, implementation issues, and baseline data collection issues. The following sub-sections describe the intended test design and, where applicable, describe changes to the test design from the demonstration plan. Details of the demonstration plan test design may be found in the demonstration plan document (Southern Research, 2010).

5.1 CONCEPTUAL TEST DESIGN

As described above (section 4.2), the existing cooling system for Building 590 consisted of a lithium bromide absorption chiller powered by central plant provided steam. The demonstrated system consisted of a silica gel adsorption chiller powered by a solar thermal panel array with backup steam and a conventional electric vapor compression chiller operated in series with the adsorption chiller to provide backup cooling or make up the balance of the building cooling load as necessary.

In essence, the conceptual test design was to evaluate the performance of the existing system before modification as a baseline and compare this to the performance of the modified system to determine energy savings. Details of this approach are provided in the demonstration plan. In addition, the performance of the overall system, as well as the performance of major sub-components of the system, was to be characterized. Major sub-components included the adsorption chiller, the solar array loop, and the DHW system.

Due to limitations of the baseline data (section 5.2) and the condition of the facility HVAC systems, energy savings could not be determined by comparison of baseline and modified system performance. Instead, the solar thermal energy input to the system was considered to offset steam input to the system and the energy savings and associated emissions reductions were determined based on this offset. To make a valid comparison, the difference in efficiency (COP) between the pre-existing absorption chiller and the new adsorption chiller is taken into account, as well as the incremental difference in parasitic electrical load between the two systems. The methodology employed to determine energy savings is given in section 6.2.3 below.

5.2 BASELINE CHARACTERIZATION

In the demonstration plan, the measured steam and electricity consumption of the existing absorption and electric chillers were to be correlated against measured cooling loads in the dining and kitchen areas, respectively. In addition, the cooling loads were to be correlated against weather data. These relationships were to be used to predict the steam and electric energy consumption of the baseline system as a function of weather and cooling load. Energy savings were to be determined as the difference in baseline and test energy inputs adjusting for weather/cooling load. These differences were to be determined on a daily or hourly basis using a methodology for mapping test data to baseline data based on cooling degree-days/hours. Details of the method proposed to relate energy consumption and cooling loads to ambient conditions were provided in a technical article prepared by Southern (Adamson, 2010).

The baseline data collected were found to be of limited representativeness and utility because, prior to construction of the new system, it was discovered that a number of existing building HVAC system subcomponents were not functioning properly (see section 4.2). The building condition would likely have confounded attempts to establish the necessary correlations between energy input and load that were necessary to the demonstration plan approach.

In addition, it was discovered that one of the baseline sensors was installed in an incorrect location due to misinformation on piping locations with the result that no valid data were collected on the cooling load of the existing absorption chiller. Finally, no data on the electric chiller baseline cooling load was collected because Southern's field team were supplied with an incorrect drawing that did not show the required sensors, with the result that the sensors were not installed. The electric chiller power consumption was measured during a later portion of the baseline monitoring period. In sum, the collected baseline data are of limited utility for determining the comparative energy savings realized from the solar chiller system.

The baseline monitoring did serve, however, to provide information on the characteristics of the existing system that were used to help troubleshoot performance issues with the existing HVAC equipment with which the new system was integrated. The baseline data also provided DHW usage information that was used as input for the design of the DHW system. Finally, the baseline monitoring provided information that helped ensure that the monitoring system for the extended test would provide valid data. Due to the limited utility of the baseline monitoring data, a new approach was developed to determine energy savings and economic and environmental benefits based on the measured solar input as offset by the incremental parasitic electrical loads between the baseline and demonstration systems (see section 6.2.3).

A summary of baseline results is provided in Appendix D of the final report.

5.3 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

The System Under Test (SUT) consisted of the following:

- Roof-mounted solar collectors intended to be capable of driving the adsorption chiller to meet 60 RT peak cooling load. Note: Vanir actually delivered a solar panel array capable of meeting a maximum 20-30 RT cooling load (depending on achieved COP of the chiller and the duration the load is required to be sustained).
- An adsorption chiller rated at 80 RT cooling capacity. The difference between the solar collector availability and capacity and adsorption chiller capacity is met using steam.
- A 1000 gallon hot water storage tank. Note: the original design called for a 6000 gallon thermal storage tank. The tank size was decreased to fit within the mechanical room, avoiding the additional piping and expense of an outdoor tank installation.
- A steam heat exchanger sized to provide sufficient energy to the adsorption chiller to meet 80 RT cooling load.
- A cooling tower sized to meet the heat removal requirements of the chiller system. Note: the original plan called for using the existing cooling tower, but it was later determined that the existing tower lacked adequate capacity.

- A solar thermal powered domestic hot water system.
- Pumps, piping, expansion tanks, a compressor, backup generator and other ancillary equipment necessary for operation of the system.
- Associated controls and instrumentation.

The existing air cooled electric chiller (60 RT capacity), formerly used solely for cooling the kitchen area, was integrated in series with the adsorption chiller to handle cooling loads in a manner intended to optimize the energy consumption and economics of the project. Although the operation of this conventional chiller is integrated with the SUT and its operational data was collected during the extended testing and partially collected during the baseline testing, the electric chiller was not formally considered part of the SUT. Schematics of the system before and after modification are provided in Appendix J of the final report.

The initial control specification was designed to maximize utilization of solar thermal energy and called for utilizing solar only or steam only to power the adsorption chiller. Utilization of available solar energy was to be prioritized in all cases. Due to the high cost of steam at the installation, the electric chiller was to be brought online before steam was brought online. Provision was made to alter the control priority should relative prices for steam and electricity change.

Due to system design issues (section 8.0), steam energy provided the base heat supply to the chiller in the demonstrated system and solar energy was utilized to increase chiller output as available. The electric chiller would make up the balance of the load as needed. Because the building cooling load was typically higher than could be met by the absorption chiller alone, the electric chiller operated and made up the balance of the load under most conditions.

5.4 FACTORY ACCEPTANCE TEST

Southern attended and observed the factory acceptance test (FAT) on July 26, 2010, at the PowerPartners manufacturing plant in Athens, GA. Southern observed four test runs; however, PowerPartners conducted numerous additional tests and provided data to Southern for a total of 32 test runs.

Southern formally accepted the chiller based on the results of run CT109. In this run, the chiller was able to maintain a COP of 0.57 at an average temperature of 160 EF and at 76T capacity using a 21 minute cycle time.

Due to integrated system design and implementation issues, none of the FAT run conditions duplicated field conditions, so it was not possible to evaluate quantitatively whether the field performance of the chiller matched FAT performance. PowerPartners has reviewed the field performance results for the chiller and, in their best engineering judgment, the field performance of the chiller was acceptable given field conditions (e.g., supply temperatures and flows to the chiller).

5.5 OPERATIONAL TESTING

The demonstration plan called for a period of controlled testing wherein the peak output of the adsorption chiller and the performance of the conventional chiller would be evaluated. Due to ongoing system redesign and reconfiguration efforts and the inability to establish system conditions comparable to the chiller submittal specifications or factory test conditions there was no occasion during the demonstration when the controlled testing could be conducted. An assessment of adsorption chiller performance based on available data is given in the final report. When operating properly, the conventional chiller consumed about 1.1 kW per RT cooling output.

Table 1 below summarizes the operating status of the test system from initial commissioning (September 2011) through the end of the demonstration monitoring period (June 2013). The only significant period of full system operation was between May and October, 2012; however, during this period, chiller performance was sub-par due to inadequate heat removal caused by insufficient condenser loop flow and (as it was later discovered), a partially plugged heat exchanger in the condenser loop. In addition, during much of this period system performance was unrepresentative because the conventional chiller installed in series with the adsorption chiller was not properly controlled, which altered, and tended to suppress, adsorption chiller output. Finally, there were fairly frequent power or steam supply outages at Building 590, which further restricted the operational periods available for evaluation.

Table 1. Operational summary.

Start Date (Time)	End Date (Time)	System Status	Notes
9/28/11 (00:00)	10/26/11 (02:30)	Intermittent operations and troubleshooting.	Not applicable (N/A)
10/27/11 (00:00)	3/20/12 (00:00)	System offline for repairs and redesign.	N/A
3/26/12 (00:00)	5/2/2012 (15:30)	Chiller operating, solar field out of service. Building steam supply limited. Hot water supply temperature to chiller was 150 EF (165 EF set point).	Chiller started on 3/20, but went down until 3/26 due to building steam system repairs.
5/2/12 (15:30)	5/16/12 (23:50)	Chiller operating, solar field out of service.	Cycle time changed from 11 minutes to 7 minutes on May 9.
5/17/12 (00:00)	5/24/12 (15:00)	Full system operating, but sub-par chiller performance due to inadequate heat removal (later determined to be caused by a fouled heat exchanger).	N/A
5/24/12 (15:00)	6/28/12 (0:00)	Full system operating, but sub-par chiller performance due to inadequate heat removal (fouled heat exchanger). Operating period not representative due to conventional chiller performance issues.	Loud bang heard on 5/24. Appears that conventional chiller was damaged. Conventional chiller power consumption was high and chilling output low.
6/28/12 (00:00)	7/15/12 (00:00)	Full system operating, but sub-par chiller performance due to inadequate heat removal (fouled heat exchanger). Operating period not representative due to uncharacteristic conventional chiller performance.	One or more conventional chiller compressors offline.

Table 1. Operational summary (continued).

Start Date (Time)	End Date (Time)	System Status	Notes
6/28/12 (00:00)	10/7/12 (15:10)	Full system operating, but sub-par performance due to inadequate heat removal (fouled heat exchanger). Operating period not representative due to conventional chiller control issues.	Conventional chiller appears to have been set to operate only at maximum output, with the result that adsorption chiller output was suppressed.
10/7/12 (00:00)	6/10/13 (00:00)	System operated intermittently for part of the remainder of October 2012, then was offline until June 2013.	N/A
6/10/13 (00:00)	6/27/13 (9:50)	Chiller only, solar field out of service.	SRI monitoring stopped at the end of this period.

SRI = Southern Research Institute

In sum, during the extended course of the demonstration, there were only a select few periods where the adsorption chiller performance could be properly evaluated. There were no operational periods when all system conditions matched the submittal specifications or factory acceptance test data for the chiller. Thus, it was not possible to determine quantitatively whether the field performance of the chiller met expectations.

5.6 SAMPLING PROTOCOL

In general, the sampling protocol consisted of continuously logged measurements of temperature and flow sufficient to determine the heat input and output (RT or British thermal units per hour [Btu/hr]) in each heat input/output of the system. These components included:

- solar heat input,
- steam heat input,
- adsorption chiller output,
- cooling tower heat removal,
- electric chiller output, and
- DHW loop heat output (from solar).

In addition, power consumption of all parasitic loads was either continuously monitored, or in the case of constant loads, spot measurements were made. These measurements included the power consumption of the:

- cooling tower fan,
- cooling tower pumps,
- chilled water pump,
- solar loop pumps,
- DHW loop pumps, and
- chiller control and auxiliary power.

Ambient conditions, including temperature, solar irradiance, and relative humidity were also monitored.

Data were logged at a 10 minute recording frequency using DataTaker DT85 data logger. Most sensors utilized 4-20 milliamp (mA) analog outputs. A total of over 40 sensor inputs were logged. The logger was connected to a cellular router with web interface that provided remote data acquisition and system configuration.

Southern downloaded and reviewed data on a weekly basis throughout the demonstration and issued status updates by email each week to all direct project participants (PIFMD, Vanir, and Power Partners). Data review consisted primarily of examination of time series plots of all parameters for each heat loop, comparison of measured and calculated values with expected results, and reasonableness and consistency checks.

When performance issues were noted, Southern requested corrective action from PIFMD, Vanir or PowerPartners, as appropriate. When issues with sensor function were detected, Southern initiated corrective action to repair or replace the failed sensors. In some cases, surrogate data were used until a sensor issue could be resolved. For example, the solar flow meter failed in early July 2012 and it was several months before the unit could be retrieved from the field, repaired and put back into service. During the interim, power consumption readings from the solar pumps were used as a surrogate for solar loop flow. This was a valid substitution since the solar loop flow known (from prior data) to be constant whenever the pumps were operating.

5.7 SAMPLING RESULTS

Monitoring data for all sensors were collected continuously throughout the demonstration. This resulted in very large data files. As discussed above, there were relatively few periods where site and system conditions were such that system performance could be properly evaluated. Detailed results for these periods are summarized in summary tables presented in Appendix H of the final report. Performance charts including an energy summary and building conditions summary are provided in Appendix I of the final report.

6.0 PERFORMANCE ASSESSMENT

Due to numerous implementation issues, few of the demonstration plan performance objectives could be fully evaluated as set forth in the demonstration plan. Given these limitations, the following sub-sections present Southern's best effort to evaluate performance for each demonstration plan objective.

6.1 SUMMARY OF PERFORMANCE OBJECTIVES AND RESULTS

Table 2 summarizes the demonstration performance objectives and results. None of the performance objectives were met.

Table 2. Performance objectives and results.

Performance Objective	Success Criteria	Results
Quantitative Performance Objectives		
Determine peak cooling capacity of the SUT	Peak cooling capacity of SUT must be greater than 80 RT	Objective not met. Maximum sustained cooling was 52.8 RT.
Determine max cooling capacity of the SUT when driven by solar energy only	When DHW solar energy demand is zero, peak cooling capacity of SUT must be greater than 60 RT without supplemental steam	Objective could not be evaluated. The final system design did not permit the system to be operated on solar output alone.
Steam energy reduction	Steam energy reduction will exceed 800 MMBtu/year including Cooling and DHW	Objective not met. Annualized net steam energy reduction over baseline was 703.8 MMBtu/yr.
Emission foot print reduction	Reductions exceed: 79 metric tons CO_2e per year relative to baseline.	Objective not met. Net GHG emissions reduction was 32.1 metric tons CO_2e per year.
Equipment availability and Reliability	>99% availability. >99% reliability.	Objective not met. Overall system availability and reliability could not be quantitatively assessed due to ongoing operational issues throughout the demonstration.
Assess economic performance	Simple payback < 7 years; Positive NPV based on ECAM and BLCC	Objective not met. Site specific payback will not be achieved within the system lifetime.
Qualitative Performance Objectives		
Determine ease of use	The average points above neutral (or above three points)	Objective could not be fully evaluated as the system did not achieve stable, routine operations during the demonstration period. The system is complex and unfamiliar. Training and documentation were incomplete as of the end of the demonstration. Implementation issues complicated operations.

6.2 PERFORMANCE RESULTS FOR DEMONSTRATION PLAN OBJECTIVES

The following sub-sections provide details on how each performance result was determined, and discuss the issues encountered in evaluating each objective. To supplement, the demonstration

plan performance objectives, a performance assessment of each of the major system sub-components (the adsorption chiller and solar array) is given in the final report.

6.2.1 Peak Cooling Capacity

The maximum sustained cooling output of the test system that was measured during the demonstration (exclusive of the contribution of the electric chiller), was 52.8 RT. This result falls short of the 80 RT performance objective. Improved cooling capacity might be achieved by optimizing the chiller cycle time set point, providing a higher hot water supply temperature or increasing condenser or chilled water flow rates. The chiller was shown to be capable of producing up to 109 RT chilling output under optimal conditions during the factory acceptance test.

6.2.2 Maximum Cooling Capacity Driven by Solar Energy Alone

Due to the reconfiguration of the system such that steam energy provided a base heat input to the chiller supplemented by solar energy as available, the chiller was not able to be driven by solar energy alone. In addition, due to the reduction in solar array capacity from the original design, the system would have been incapable of meeting the building cooling load on solar energy alone. For these reasons, it was not possible to evaluate the maximum cooling capacity of the system when the chiller was driven by solar energy alone. The final report provides a first order estimate of the cooling capacity of the installed system when driven by solar energy alone based the chiller COP and the maximum measured output of the solar field.

6.2.3 Steam Energy Reduction

Due to the limitations of the baseline data (see Section 5.2), and given the few periods when the installed system was operating near specification, it was not possible to apply the demonstration plan strategy for determining the steam energy reduction. Therefore, the only means available to estimate the steam energy reduction is to regard the solar energy input to the buffer tank as an offset to energy that would otherwise have been supplied by steam. Caveats and limitations for this approach are discussed in the final report.

Because the solar field was never operational over the course of a complete year, a method was developed to annualize solar energy input to the system based on a standard industry model for forecasting the performance of solar thermal arrays. Based on this combination of measured and modeled results, the most representative value of gross annual solar energy input to the system is 914.9 MMBtu/year.

If the achieved COP of the adsorption chiller is taken as 50%, the relative COP of the test versus baseline chiller is 50/65 or 76.9%. Thus, the net steam energy reduction for the test system would be 76.9% of 914.9 MMBtu/year, or 703.8 MMBtu.

This value (703.8 MMBtu/year) approaches the success criteria of 800 MMBtu/year for the steam energy reduction; however, due to the uncertainties in the analysis, it cannot be stated for certain whether the success criteria was achieved or not achieved. For example, if the achieved COP for the test chiller had been somewhat higher or the COP of the baseline chiller had been

somewhat lower, the criteria might have been met. For example, if the COP for the adsorption chiller had been at the acceptance test condition (57%), the steam energy reduction would have been 802.3 MMBtu/year – just meeting the success criterion.

The values and calculations in the discussion above are provided in the final report.

6.2.3.1 Domestic Hot Water

The foregoing analysis does not include consideration of any steam energy reduction due to the solar DHW system installed at Building 590. As the DHW system was not completed and operational before the end of the demonstration monitoring period, no assessment based on actual monitoring data can be made.

Using a DHW diurnal load profile supplied by Southern from baseline monitoring data, Vanir Energy modeled the performance of the DHW system, as installed. In summary, the available solar energy is sufficient to provide approximately 56% of the DHW demand at Building 590 on a year-round basis, and about 46.5% during the winter months (November through February). That said, due to the cyclical nature of DHW demand at Building 590 (three daily peaks corresponding to meal preparation), the solar field would stagnate after the first peak each day and no longer be able to provide heat input to the DHW system. Therefore, the actual heat recovery from the solar field for DHW use would be only about 1/3 of the potential. The solar array currently has no provision for dumping excess heat to prevent stagnation; however, such a provision would increase the fraction of available solar array output that could be utilized for DHW.

Under current building management rules at Parris Island, the cooling system at Building 590 is operational year-round and can readily consume all of the available solar energy even in winter months. So, under current building management rules, it is not expected that the DHW system will contribute at all to solar thermal utilization and steam energy reduction.

6.2.3.2 Parasitic Loads

In addition to the steam energy reduction, the test system had the potential to reduce the electrical demand of the cooling system at Building 590. For example, the demonstration called out the low electrical demand of the absorption chiller as an advantage of the system. The existing absorption chiller consumed 5 kW while the new adsorption chiller demands only 0.67 kW (including controls and an auxiliary air compressor and dryer). In addition, the cooling tower fan load on the new system was reduced by employing a variable frequency drive (VFD) controlled fan that only consumes as much power as necessary to provide the necessary cooling.

However, the new system has additional pumps for the solar loop, plus an additional pump on the cooling tower loop as this loop is divided by a heat exchanger to prevent the open cooling tower water from contaminating the cooling water entering the adsorption chiller. Moreover, in the spring of 2013, the cooling tower loop pumps were increased from 7.5 horsepower (HP) to 15 HP in an effort to increase the cooling loop flow to achieve the expected output from the adsorption chiller. The net effect is that the electric power consumption of the new system significantly exceeds that of the baseline system. Baseline system parasitic loads totaled 23.3

kW. Test system parasitic loads totaled 36.7 kW. The breakdown of parasitic load by component is provided in appendices to the final report. The net parasitic loads for the test system versus baseline is 13.4 kW on a continuous basis. With the original 7.5 HP pumps, the net parasitic load was only 2.1 kW. This difference is taken into account in determining the emission footprint reduction in section 6.2.4 below.

Note that the net parasitic load will be site specific as this depends on the retrofit system configuration as well as particulars of piping head pressure in each loop for a given site.

6.2.4 GHG Emission Footprint Reduction

The GHG emission footprint reduction attributable to the solar chiller system compared to the baseline system is the result of the following: 1) the decrease in natural gas usage attributable to the steam energy reduction, and 2) the change in parasitic load between the baseline and test system. The considerations taken into account in determining GHG emissions reductions associated with each of these factors are presented in the sub-sections below. The decrease in natural gas usage is associated with a GHG emissions reduction of 76.3 metric tons CO_2e per year. There was an increase in electricity consumption of the installed solar chiller system over the baseline system that is associated with a GHG emissions increase of 44.1 metric tons CO_2e per year. Thus, the net GHG reduction is 32.1 metric tons CO_2e per year, which is significantly short of the 79 metric ton CO_2e GHG reduction goal.

Details of the considerations, calculations and values used in this determination are given in the final report.

6.2.5 Availability and Reliability

It was not possible to quantitatively assess the availability and reliability of the installed system because the system did not operate fully as intended at any time during the demonstration. The 99% goals for availability and reliability were not demonstrated.

For the most part, the absorption chiller operated successfully throughout the demonstration whenever its operation was supported by the necessary sub-components of the system (the steam/solar loop, the cooling tower loop and the chilled water loop). Initially, there was a minor vacuum leak on the chiller that reduced performance, but did not result in an outage. The vacuum leak was associated with a removable water column that was bolted on to the chiller to allow it to fit through the mechanical room door at Building 590 for installation. This configuration was particular to the Parris Island installation. In most installations, the water column is welded in place. The leaks were promptly repaired by PowerPartners following installation. There was a chiller outage in April 2012 caused by the chiller controls failure to reload site specific set points following a power outage. This issue was promptly corrected by PowerPartners who reprogrammed the system to reload the correct default values following an outage. These were the only operability issues associated with the chiller.

The solar system was continuously operable over only an approximate 5 month period (May 16-October 7, 2012) out of 20 months of monitoring (October 2011 through June 2013), beginning with the initial system commissioning. The solar panels themselves performed as expected;

however, the balance of the solar loop suffered problems with piping leaks, over-pressurization, expansion tank capacity, air infiltration, and faulty pressure relief valves. In addition, Vanir Energy failed to respond as promptly as would be expected to correct issues as they arose.

6.2.6 Economic Performance

The solar chiller system installed at Parris Island was not cost effective. Net energy consumption costs for the test system were higher than baseline. There was a small, overall net savings associated with the test system resulting from lower maintenance costs of the adsorption chiller compared to the absorption chiller. However, the savings was not large enough for the system to realize a payback over its lifetime. Details of the economic analysis are presented in section 7.0.

6.2.7 Operability/Ease of Use

According to the demonstration plan, ease of use was to be assessed based on responses to a brief questionnaire from PIFMD management and maintenance personnel. Southern received no responses to the questionnaire. However, Southern was on site at every stage of the installation and operation of the system and had frequent interactions with PIFMD management and maintenance staff through face to face communication, and telephone and email contact. These interactions were documented via trip reports, responses from PIFMD to weekly status updates and implementation issues, and monthly status reports. Thus, Southern feels that it is in a good position to offer a fair assessment of the operability and ease of use of the system.

The adsorption chiller operates automatically and the controls, though initially unfamiliar to PIFMD, are straightforward and accessible via the touch screen control panel. Southern attended training provided by PowerPartners to PIFMD management and staff during initial commissioning in September 2011. The training was complete and well-presented and included both theoretical and operational information. A classroom training session was followed by hands on field training. Full documentation of chiller operation and maintenance was provided.

Southern's assessment is that, with proper documentation, training and operating experience, the system will be successfully operated and maintained by PIFMD maintenance staff. However, as the system is fairly complex and somewhat unfamiliar to PIFMD maintenance staff, ongoing support may be necessary. While the system, as designed, should be able to operate automatically and unattended, there are nuances of the system configuration that require a full understanding of the system function, as implemented, to effectively troubleshoot problems and minimize downtime.

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7.0 COST ASSESSMENT

The solar chiller system installed at Building 590 was not cost effective. The reasons for this include:

- The installed capacity of the solar array was about 50% smaller than the design capacity so the associated steam energy reduction and natural gas savings were not sufficient to offset the capital and operating costs over time.
- The electric demand of the test system was higher than the baseline system. The increase in electric cost was higher than the natural gas cost savings.
- Maintenance costs for the adsorption chiller are considerably lower than that for the baseline absorption chiller, resulting in a small net savings for the test system at Building 590 compared to baseline. However, this savings is not large enough to provide a payback within the lifetime of the system.

Based on Southern's experience with this demonstration and recent findings from other researchers (Dickinson, et al., 2010; Ishaya, 2011), a solar thermal chiller system based on evacuated tube collectors is unlikely to be cost effective under most implementation scenarios, especially as compared to alternative solutions (Section 7.3.3).

The following sections provide details supporting these conclusions.

7.1 COST MODEL

The cost model for the solar chiller technology accounts for initial capital costs (including engineering and installation) and routine operation and maintenance costs. The demonstration plan baseline economic assumption is that the energy savings are intended to recover the capital and operation and maintenance (O&M) costs of the entire retrofit installation. This report also addresses an alternative baseline economic assumption that the energy savings need only be sufficient to recover the differential cost between the retrofit system and in kind replacement of the existing system.

7.1.1 Capital Costs

The Vanir invoiced costs for the system totaled $772,672 including engineering, equipment and installation. These costs may be taken as representative of a typical 'turn-key' installation consistent with the bid package specification. In addition, there were costs totaling $41,000 to replace the aging cooling tower and install control sensors (including wiring and programming) that were covered by additional project funds or by PIFMD. Thus, the initial installed cost for the complete system totaled $813,672. A breakdown of these initial costs is given in the final report.

In addition to quoted costs, a number of cost over-runs were encountered during commissioning of the solar chiller system at Building 590. These costs were primarily related to repairs to the solar field due to over-pressure and over-temperature conditions that were encountered. There were also additional costs for larger cooling tower loop pumps and a larger steam valve that were installed in an effort to realize the rated output of the chiller. Vanir's actual expenditures totaled

$814,052, or $41,380 over the fixed bid price. Parris Island bore the cost of installing the larger cooling tower loop pumps, motor controls, and the larger steam valve. Southern does not consider the over-run costs as representative because they reflect deficiencies in the initial system design that could be avoided in future implementations.

7.1.2 Operation and Maintenance Savings

Routine operation and maintenance costs could not be tracked as the system did not achieve routine operation during the demonstration. Table 3 gives incremental O&M cost estimates provided by Vanir Energy and PowerPartners for test system components over the baseline absorption chiller. Costs are primarily for labor for inspections and adjustments as there are few required replacement parts and no consumables. A labor rate of $65/hour was applied.

Table 3. Incremental operation and maintenance savings.

Item	Cost	Notes
Adsorption chiller	$3000	PowerPartners estimate
Solar Array	$4160	Vanir Estimate
Solar DHW	$520	Vanir Estimate
Controls	$1040	Vanir Estimate
Total	**$8720**	Sum
Absorption chiller	$15,000	PowerPartners figure
Incremental O&M savings over baseline	**($6280)**	Cost savings

Because of the high estimated annual O&M cost for the absorption chiller, the O&M costs for the test system are lower than for the baseline system.

Non-annual maintenance or replacement costs for the test system are minimal. Vanir recommends that the solar controller be replaced after 5 years at a cost of $5,000.

7.1.3 Service Life

Southern determined the service life for the test system at 20 years based on published American Society of Heating Refrigeration and Air-conditioning Engineers (ASHRAE) median service life data for major HVAC system components (ASHRAE, 2012), adjusted downward for the coastal environment at Parris Island. Vanir concurred with Southern's estimate.

7.2 COST DRIVERS

The solar chiller technology will not be cost effective unless there is sufficient solar radiation to power the system and offset sufficient electric or other fuel consumption to provide a payback in a reasonable period. The energy consumption of the entire system including pumps, heaters and controls must be carefully evaluated to ensure a net savings is realized. Compared to Parris Island, a higher radiation area, such as the Southwest U.S. where annual solar radiation is approximately twice that in South Carolina, would yield a higher return on investment.

The candidate building must have sufficient solar exposure and available rooftop or adjacent area for the solar collector array. Solar array racking costs were increased at Parris Island over other

locations due to the need to withstand hurricane force wind loads. In areas with similar solar radiation to Parris Island, an array approximately twice the size of that employed at Parris Island (4500 square feet) could be effectively utilized for an equal tonnage cooling system. It is generally uneconomical to size the solar array larger than can be effectively utilized to offset solar induced cooling loads.

The candidate building must have sufficient space available to house the chiller, storage tank, and balance of plant equipment. The EcoMax adsorption chiller may be installed outdoors.

Solar thermal chiller systems should be carefully evaluated against alternative solar cooling options such as solar photo voltaic (PV)/vapor compression chillers, which in many instances, may be more cost effective.

7.3 COST ANALYSIS

Net annual savings and system payback are examined from several perspectives in the following sub-sections. First, economic results are presented for the Parris Island installation with the demonstration plan baseline assumption that capital costs were to be entirely recovered from energy savings. Next, an assessment is presented based on the differential cost compared to a replacement in kind with new equipment of the same type. Finally, several alternate system performance scenarios are examined to determine whether probable improvements in system performance will result in acceptable economics.

7.3.1 Parris Island Installation

There was no net energy cost savings for the test system over baseline as the natural gas cost savings due to the steam energy reduction were overshadowed by increased electricity usage of the test system over baseline. Estimated annual O&M costs for the test system are lower than the baseline system due to the lower maintenance costs for the adsorption chiller over the baseline absorption chiller. These two factors result in a small net cost savings of the test system over baseline of about $2900 per year. This amount is clearly insufficient to recover the approximate $800,000 capital cost of the installed system over a 20-year service life.

The data and calculations supporting this conclusion are presented in the final report.

Early estimates projecting a 7 year payback for the system did not anticipate that the electric usage for the test system would be significantly higher than the baseline system and assumed a much higher solar contribution than was realized given the reduction in solar array capacity. In addition, at the outset of the project, the Parris Island steam cost was very high ($41.85/MMBtu based on FY2009 activity rate), which led to under-estimates of the system payback period. This value includes the high cost of operating and maintaining Parris Island's aging steam plant and distribution system.

The steam cost was later revised significantly downward to $6.42/MMBtu (FY2012 activity rate) in response to concern from private party rate payers at the installation. This value is representative of the cost of the natural gas used to produce central plant steam, excluding distribution losses. The energy savings results given above are based on the cost of natural gas to

produce a given quantity (MMBtu) of steam as delivered to the chiller accounting for boiler efficiency, distribution losses, and heat exchanger efficiency. As Parris Island does not currently account for the operating and maintenance cost for steam generating and distribution, these costs are neglected. Steam plant and distribution system O&M costs are highly site specific and representative information on such costs is not readily available.

Part of the reason there was no net revenue for the Parris Island installation is that the solar field capacity was reduced by about 50% from the original project specification, so the steam energy reduction and associated natural gas savings were substantially lower than they might have been. Another contributing factor was that the demonstrated efficiency (COP) of the adsorption chiller was lower than the assumed efficiency for the baseline absorption chiller.

Because there was insufficient net savings for the test system compared to baseline to yield a payback period within the system lifetime, a more detailed life cycle cost analysis for the Parris Island solar chiller installation was not warranted under the demonstration plan assumption that the entire retrofit cost was to be recovered through energy savings. The following sections consider an alternative approach to the cost assessment and examine system economics under selected scenarios for optimizing system performance.

7.3.2 Differential Cost Analysis

The baseline scenario for the economic assessment might reasonably have been to consider the differential cost between the solar adsorption chiller system and replacement in kind with a steam driven absorption chiller. This approach is consistent with industry practice and, as stated above, the existing absorption chiller and cooling tower at Building 590 were nearing the end of their useful life. Thus, it is reasonable to assume that this equipment might have been replaced in any case.

According to data from PowerPartners, the cost of an absorption chiller of similar capacity to the old chiller at Building 590 (90 RT) would be about $130,000. The 80 RT rated adsorption chiller cost to the project was $191,000, so the differential cost is $61,000. Because the cooling tower would also have been replaced in the baseline case, the differential cost of the cooling tower is zero.

It is more difficult to estimate the differential cost of balance of plant equipment such as pumps, piping, and controls. However, it is reasonable to assume that there would be significant costs to update the old system balance of plant components with a replacement absorption chiller installation.

An estimate of installed capital costs in a differential cost scenario is developed in the final report. A differential cost factor is used to apportion the cost for each capital cost item. A differential cost factor of 30% of the total retrofit cost is considered as a base. The 30% factor is consistent with the differential cost for the chiller as discussed above ($61,000/$191,000 = approximately 30%) and is also consistent with Vanir experience with other installations. The base factor is adjusted upward for items where the line item costs are more associated with the solar part of the system. A differential cost factor of one (1.0) indicates that the capital cost item is associated with the solar portion of the system only.

Based on this analysis, the differential capital cost of the solar thermal chiller system is about $460,000. This is a very approximate figure, but the methodology may be useful to some in assessing site specific cost-effectiveness for future solar thermal chiller systems installations.

7.3.3 Alternative Performance Scenarios

Because the performance of the Parris Island system was non-optimal, it is useful to consider alternative scenarios where performance may be improved. Specifically, if any of the following had been the case for Parris Island installation, system economics could have been improved.

- Replacement of the original 7.5 HP tower loop pumps with the 15 HP had been unnecessary, reducing the net parasitic load from 13.4 kW to 2.1 kW.
- The chiller COP had been demonstrated at the acceptance test performance level (0.57).
- The full 60 RT chilling capacity of the solar field had been installed.

Finally, the hypothetical case is considered where a similar system is located in the desert Southwest where there is approximately twice the annual solar irradiance to that at Parris Island.

Table 4 gives annual energy savings and net annual savings (including O&M savings) for each alternate scenario. The table also shows the simple payback period for both total retrofit cost recovery and differential cost recovery baseline assumptions.

Table 4. Economic projections for alternate performance scenarios.

Scenario	Net Annual Energy Savings	Net Annual Savings (Incl O&M)	Simple Payback for Total Retrofit Cost Recovery (years)	Simple Payback for Differential Cost Recovery (years)
Demonstrated Parris Island Performance	($3372)	$2908	280	158
With original 7.5 HP tower loop pumps	$4482	$10,762	76	43
At acceptance level absorption chiller COP (0.57) and 7.5 HP pumps	$5315	$11,595	70	40
At acceptance level absorption chiller COP (0.57) and 7.5 HP pumps and full specified 60 RT solar field capacity	$12,108	$18,388	44	25
At acceptance level absorption chiller COP (0.57) and 7.5 HP pumps, full specified 60 RT solar field capacity and maximum solar irradiance (e.g., Southwest United States)	$25,680	$31,960	25	14

Note: Capital cost for total retrofit cost recovery is $813,672. Capital cost for differential cost recovery is $460,000. Natural gas cost at $4.22/MMBtu per Energy Information Administration (EIA) 2012 for South Carolina.

Under the best case scenario, simple payback would occur in year 14. This is the only case where payback occurs within the expected service life of the equipment.

7.4 COST COMPARISONS

Adsorption chillers are roughly twice as costly as absorption chillers on a ton for ton capacity basis. This is partly because of a more limited market penetration of adsorption chillers and partly due to higher materials and manufacturing costs. For the Parris Island demonstration, the cost of the existing absorption chiller was considered a sunk cost and did not figure into the demonstration cost analysis. However, for a new system, if hot water supply temperatures can be maintained high enough (above 180°F), an absorption chiller might be a more economical choice.

Conventional electric powered vapor compression chillers have still lower initial capital cost per refrigeration ton capacity than either adsorption or absorption chillers. With low current photovoltaic panel costs, a photovoltaic powered vapor compression system may often be a better economic option for a solar chilling system. A further economic advantage of solar electric chilling systems is that solar thermal chiller systems require backup chilling capacity, usually in the form of a vapor compression chiller, as it is typically uneconomical to size a solar thermal array and storage to provide 100% of the required chilling capacity for a building. Another advantage of solar photovoltaic is that a grid-tied system can easily and cheaply take up any excess PV capacity.

8.0 IMPLEMENTATION ISSUES

There were a number of technical and management issues that negatively impacted the success of the demonstration. In general, the issues may be summarized as follows.

There were a large number of issues with the original system design. Examples include:

- The available roof area was insufficient to support the planned solar thermal capacity.
- The initial design for chiller operation on solar or steam energy alone was unworkable.
- The design failed to account for water transfer between the hot water and tower loops within the chiller (though this fact was documented in the chiller manual).
- The solar field piping design and construction did not make adequate provision for high temperatures during stagnation events.
- The initial piping design had inadequate provision for pressure relief and release of entrapped air.
- The initial control sequence was incomplete, which caused delays in system commissioning.
- The design failed to make adequate provisions to ensure that chiller supply flows and temperatures would meet the chiller submittal specifications.

Essentially, the original design was incomplete and inadequate and Southern failed to ensure that a full design review was completed, and the design fully documented and approved, prior to the start of construction.

It is important that the selected technology vendor buys in to the demonstration nature of the project and that this commitment is reflected explicitly in the scope of work and contract. In addition to supplying the necessary equipment, engineering expertise and installation services, the vendor must support achieving demonstration objectives by providing, for example, engineering analyses and economic data and being responsive to meeting the objectives of the demonstration. As an example, Vanir's delays in completing the DHW system installation prevented evaluation of DHW system performance.

While a large number of chiller test runs were completed at the factory, the factory acceptance test conditions matrix did not anticipate the range of possible supply flow and temperatures to the chiller that might be encountered in the field, or span the range of chiller cycle timing that might be employed to optimize performance under field conditions. This made it impossible to fully evaluate whether the field chiller performance was within the expected range and complicated efforts to optimize chiller performance in the field. This shortcoming was partly a consequence of Southern's failure to ensure that the system design was complete prior to implementation.

There were also issues with building HVAC systems maintenance that impacted Southern's ability to fully evaluate the performance of the test system. In particular, the electric chiller was

not controlling properly throughout most of the 2012 cooling season (May through October) such that the absorption chiller performance was unrepresentative during much of this period. Because the two chillers are installed in series, if the electric chiller is running at full output without responding to demand then the output of the adsorption chiller will be suppressed. This period happens to correspond with the only lengthy continuous period of operation of the full solar chiller system. In addition, the solar chiller system was down for nearly 6 months (October 2013 through March 2013) due to the time required to clean the tower loop heat exchanger. The heat exchanger was fouled because the cooling tower water treatment system was removed when the new tower was installed and not replaced.

Regulatory barriers for solar chiller installations are low. The project must meet local building and fire codes. At Building 590, there were significant costs associated with meeting the required hurricane wind load for the rooftop panel installation.

The end-user (PIFMD) concern was keeping the building cool and potentially realizing a renewable energy benefit. Although the system was not demonstrated to perform to expectations, indoor temperatures were maintained at set point. PIFMD also benefited in that the new equipment (primarily the chiller and cooling tower) replaced existing equipment that was nearing the end of its useful life. Southern left in place equipment to monitor the solar field input to the system so that PIFMD may quantify the renewable energy benefit.

It is worth noting that the problems encountered during the Parris Island demonstration are not unique. In a 2012 report (Navarro-Rivero and Ehrismann, 2012), the Quality Assurance in Solar Heating and Cooling Technology (QAiST) group of Intelligent Energy Europe surveyed 57 solar cooling installations in 10 European Union (EU) countries. The survey was especially focused on durability, maintenance and cost issues. The report notes many of the same issues encountered during this demonstration including:

- building maintenance issues,
- insufficient flow rates,
- lack of solar field capacity,
- leakage resulting from stagnation events,
- lower than expected chiller capacity and COP,
- heat exchanger and pipe fouling, and
- chemical treatment failures.

9.0 REFERENCES

ASHRAE Service Life Query Dataset, http://xp20.ashrae.org/publicdatabase/, 2002.

CTS Inc., "PIMCRD Building 590 Air Handler Repair List," February 2011.

Dickinson, et al., "Cost and Performance Analysis of a Solar Thermal Cooling Project," Proceedings of the ASME 2010 4th International Conference on Energy Sustainability, May 17-22, 2010, ES2010-90248.

Frederic A. Hooper, Jr. and Ronald D. Gillette, "How Efficient Is Your Steam Distribution System?" http://www.trapo.com/howeffic.htm, October 2012.

Gary Phetteplace, "Efficiency of Steam and Hot Water Heat Distribution Systems," US Army Corps of Engineers Cold Regions Research & Engineering Laboratory, September 1995.

Ishaya, S., "Solar Cooling Methods and Applications," Presentation, Pragmatic Professional Engineers, July 2011.

Pilar Navarro-Rivero and Björn Ehrismann, "Durability issues, maintenance and costs of solar cooling systems," Task Report 5.3.2. QAiST, Intelligent Energy Europe, May 2012.

PowerPartners, "Parris Island 8/7/12" presentation, August 2012.

Richard Adamson, Southern Research, "Technical Note: Projecting Heating or Cooling Energy Usage or Savings," April 2010.

Southern Research, "Demonstration Plan: Demonstration of a Solar Thermal Combined Heating, Cooling and Hot Water System Utilizing an Adsorption Chiller for DoD Installations," July 2010.

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APPENDIX A

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