ERDC TR-23-25

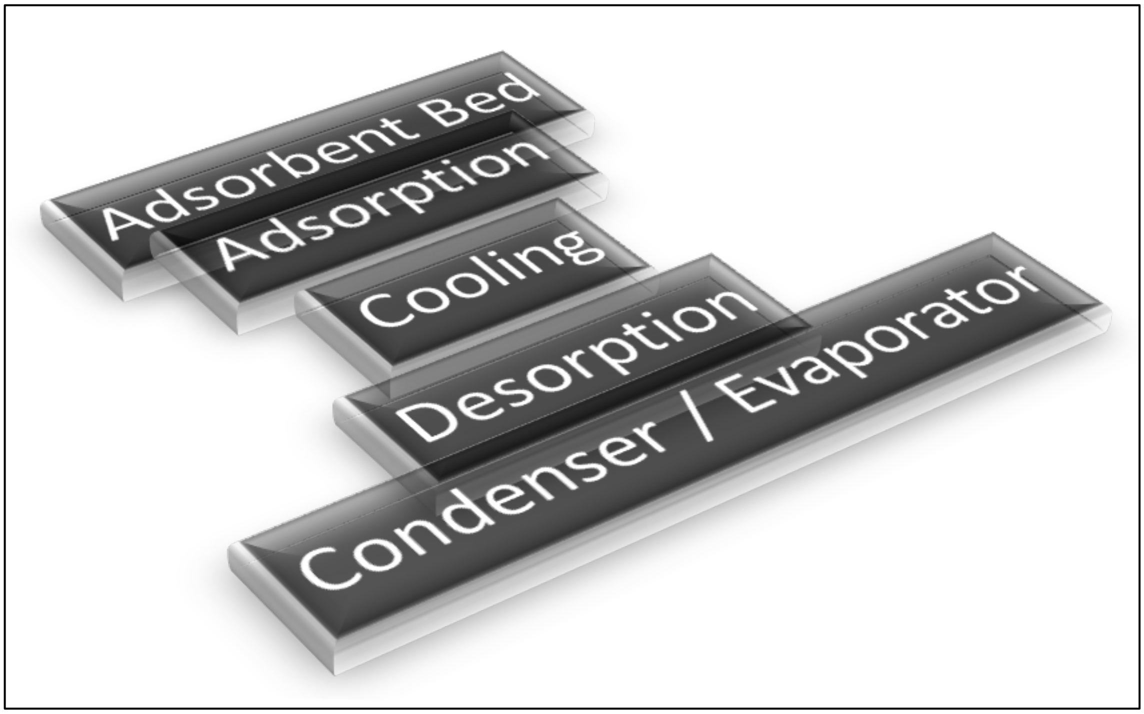
Engineer Research and Development Center

*Installation Technology Transition Program*

# Investigation of Steam Adsorption Chillers to Modernize Existing Central Steam Plant Systems

Melisa Nallar, Shelia K. Barnett, Edith L. Martinez-Guerra, Jamie T. Potter, and Christina H. Rinaudo

November 2023



Installation Technology Transition Program

**ERDC TR-23-25**
**November 2023**

# Investigation of Steam Adsorption Chillers to Modernize Existing Central Steam Plant Systems

Melisa Nallar and Jamie T. Potter

*US Army Engineer Research and Development Center (ERDC)*
*Cold Regions Research and Engineering Laboratory (CRREL)*
*72 Lyme Road*
*Hanover, NH 03755-1290*

Shelia K. Barnett and Christina H. Rinaudo

*US Army Engineer Research and Development Center (ERDC)*
*Information Technology Laboratory (ITL)*
*3909 Halls Ferry Road*
*Vicksburg, MS 39180-6199*

Edith L. Martinez-Guerra

*US Army Engineer Research and Development Center (ERDC)*
*Environmental Laboratory (EL)*
*3909 Halls Ferry Road*
*Vicksburg, MS 39180-6199*

Final Report

Distribution Statement A. Approved for public release: distribution is unlimited.

Prepared for Deputy Chief of Staff, G9
Installation Technology Transition Program (ITTP)
Army ACSIM Management Support Office
600 Army Pentagon
Washington, DC 20310-0600

Under MIPR 11681657

# Abstract

This report investigates the integration of steam adsorption chillers as a modernization strategy for conventional central steam plant systems. Our objective is to assess the feasibility, advantages, and challenges of incorporating steam adsorption chillers into existing steam plant setups to enhance energy efficiency and cooling capabilities. Central steam plant systems have historically been used for steam-based heating but often lack cooling capabilities, necessitating additional cooling infrastructure. Steam adsorption chillers offer a potential solution by using waste steam for cooling, optimizing energy utilization and reducing reliance on traditional cooling methods. Through a comprehensive analysis, this report evaluates the technical compatibility and potential cost implications of implementing steam adsorption chillers. It explores factors such as system integration, operational dynamics, and maintenance requirements to provide a holistic view of the feasibility and benefits of this modernization approach. The findings aim to offer valuable insights to decision-makers and Army facility managers seeking innovative ways to upgrade central steam plant systems. By considering the technical and economic aspects of adopting steam adsorption chillers, this report contributes to the knowledge base for sustainable and efficient energy utilization in central plant operations.

# Contents

**Abstract** ii

**Figures and Tables** iv

**Preface** v

**1 Introduction** 1

1.1 Background 2
1.2 Objectives 3
1.3 Approach 3

**2 A Comparative Analysis: Conventional Chillers vs. Adsorption Chillers** 4

**3 Engineer Research and Development Center's (ERDC) Investigation at Lake City Army Ammunition Plant (LCAAP) in FY23** 8

3.1 Available System at the Site 8
3.2 Current Energy Consumption 10
3.3 Potential for Adsorption Chillers 14

**4 Cost Analysis** 15

4.1 Cost Analysis of Adsorption Chiller compared to Absorption Chiller 15
4.2 Breakeven Analysis for notional comparison of Adsorption Chiller and LCAAP Centrifugal Chiller 19

**5 Conclusions and Recommendations** 22

5.1 Recommendations 22
5.2 Conclusions 23

**Bibliography** 24

**Abbreviations** 25

**Report Documentation Page (SF 298)** 26

# Figures and Tables

## Figures

1. Adsorption chiller. (Image reproduced from Hansen et al. 2013. Public domain.) ............ 2
2. Energy distribution and cost in 2021. ............ 11
3. Energy consumption and cost reported on the last quarter since FY13. ............ 12
4. Energy consumption and cost per chiller at Lake City Army Ammunition Plant (LCAAP). ............ 13
5. Cost to benefit—breakeven analysis for adsorption versus absorption chillers. ............ 17
6. Cost to benefit—breakeven analysis for adsorption versus LCAAP centrifugal chillers. ... 21

## Tables

1. Conventional and adsorption chillers comparison. ............ 5
2. Commercially available chillers comparison. ............ 6
3. Utility rates at Lake City Army Ammunition Plant (LCAAP). ............ 14

# Preface

This study was conducted for the Deputy Chief of Staff, G-9, Installation Technology Transition Program, under MIPR 11681657, entitled "Investigation of Steam Adsorption Chillers to Modernize Existing Central Steam Plant Systems." The technical monitor was Ms. Natalie R. Myers, Engineer Research and Development Center–Construction Engineering Research Laboratory (ERDC-CERL).

The work was performed by the Engineering Resources Branch of the Research and Engineering Division, ERDC–Cold Regions Research and Engineering Laboratory (CRREL). At the time of publication, Dr. Melisa Nallar was branch chief; and Dr. John W. Weatherly was acting division chief. The deputy director of ERDC-CRREL was Dr. Ivan P. Beckman, and the director was Dr. Joseph L. Corriveau. The work was also performed by the Institute for Systems Engineering Research Branch of the Computational Science and Engineering division, ERDC–Information and Technology Laboratory (ITL). At the time of publication, Mr. Willie H. Brown was branch chief; and Dr. Jeffrey L. Hensley was division chief. The deputy director of ERDC-ITL was Dr. Jackie Pettway, and the director was Dr. David A. Horner. The work was also performed by the Environmental Engineering Branch of the Environmental Processes Engineering division, ERDC–Environmental Laboratory (EL). At the time of publication, Dr. Michael Rowland was branch chief; and Mr. Warren Lorentz was division chief. The deputy director of ERDC-EL was Dr. Brandon J. Lafferty, and the director was Dr. Edmond J. Russo Jr.

COL Christian Patterson was commander of ERDC, and Dr. David W. Pittman was the director.

# 1 Introduction

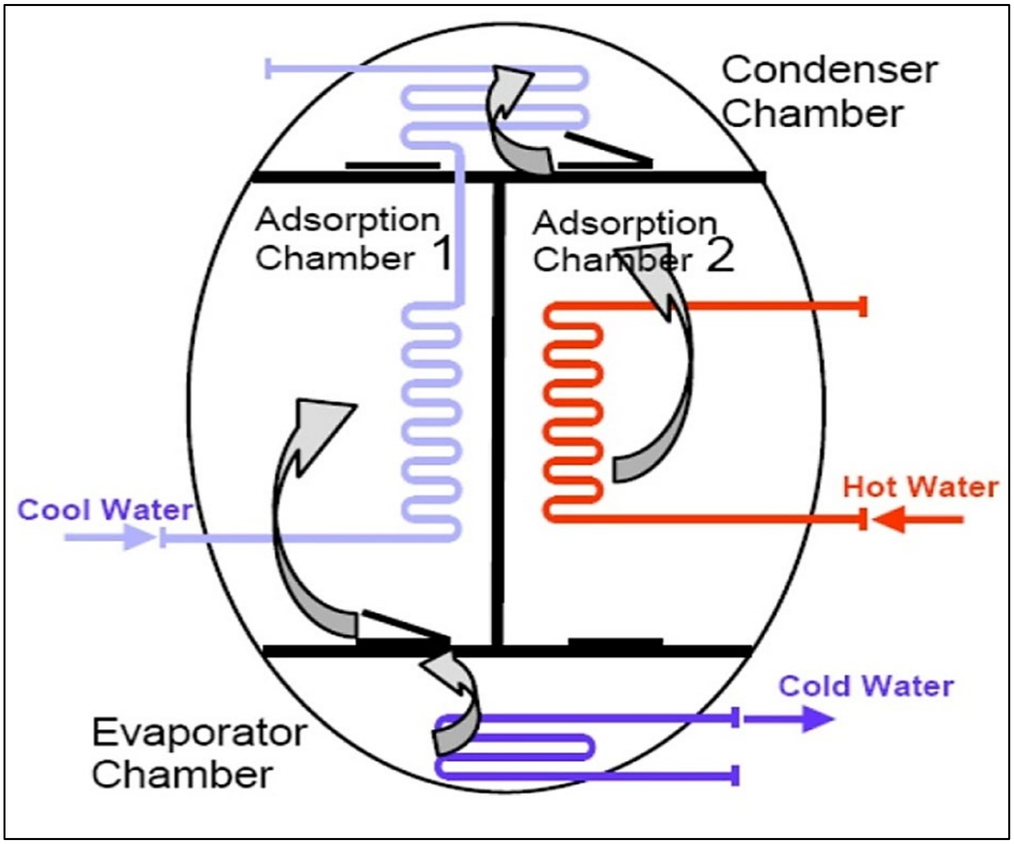
Chillers are a large energy consumer on many DoD installations. A chiller is a refrigeration system that removes heat. They are typically used for lowering the temperature of fluid that is used to cool either equipment or internal spaces of buildings. Industrial uses include cooling water used in machinery and manufacturing processes (Hansen et al. 2013).

Improving the efficiency of chiller systems on an installation can reduce energy consumption and costs and positively impact installation energy resilience. Chillers can be designed for a range of temperature, size, and other requirements. Different types of chillers exist such as vapor-compression, absorption, or adsorption. All chillers use thermodynamic principals of phase change to transfer heat from one location to another (Gado et al. 2021).

Adsorption chillers operate by utilizing adsorption, a process that involves the adherence and release of a thin refrigerant layer onto the surface of a solid material, as depicted in Figure 1. This mechanism encompasses both endothermic (cooling) and exothermic (heating) phases. Notably, this method presents several advantages compared to alternative chiller technologies, including reduced noise, resistance to corrosion, and the use of environmentally friendly materials. (Goyal et al. 2016) Common solid sorbents employed in these chillers encompass activated carbon, silica gel, and zeolite. (Freni et al. 2016).

Adsorption chillers can utilize waste heat from an installation’s central energy plant (CEP) to drive the adsorption chiller process. This efficiently uses an installation’s existing resources to achieve its cooling demands.

Figure 1. Adsorption chiller. (Image reproduced from Hansen et al. 2013. Public domain.)



## 1.1 Background

CEPs are commonly used on military installations for facility heating and cooling. However, many of these systems suffer from low efficiency because of aging components and failing pipelines. To address these inefficiencies, system improvements can be made to increase the usability of energy sources and reduce operating costs, as well as improve reliability.

One potential improvement is the use of adsorption chillers. These chillers can be powered by waste heat, such as excess steam from a CEP, or heat generated by solar panels or other devices. Unlike traditional refrigeration systems, adsorption chillers use only water as the refrigerant and an adsorbent, eliminating the need for chemical refrigerants and the associated maintenance and safety concerns (Gado et al. 2021).

Adsorption chillers follow a multi-step operational cycle encompassing adsorption, heating, desorption, and cooling processes. In the heat pumping phase, the adsorbate vapor, sourced from the evaporator, is conveyed to the adsorption bed. In this journey, it absorbs heat, effectively cooling the bed. Following this, an external heat source is introduced to the system, causing a substantial increase in both temperature and pressure within the bed. This elevation in conditions initiates the desorption of the adsorbate vapor. The vapor subsequently proceeds into the condenser unit, where it undergoes a transformation, releasing its stored heat and transitioning into a liquid state. This liquid is then utilized for the purpose of regenerating the adsorption bed. (Hansen et al. 2013)

Adsorption chillers have several advantages over traditional refrigeration systems, including energy efficiency, minimal running costs, long life, easy maintenance, and use of natural refrigerants. The technology is also driven by heat rather than electricity, making it a desirable solution for clean energy generation. Additionally, adsorption chillers can be easily disposed of at the end of their lifespan.

While optimal performance is achieved during the cold season, adsorption chillers are still a viable and environmentally friendly solution for cooling spaces. By using local district heating systems to power the chillers, they can supply the demand of district cooling networks. Overall, the use of adsorption chillers has the potential to greatly improve the efficiency and reliability of central cooling systems on military installations.

## 1.2 Objectives

This project aims to offer an assessment of implementing steam adsorption chillers in central heating and cooling plants. The ultimate goal is to empower decision-makers to make more informed choices when considering efficiency enhancements for existing cooling plant systems at Army installations.

## 1.3 Approach

The project consisted of three parts, (1) data collection, (2) system analysis or comparison between conventional and adsorption chillers, and (3) cost analysis. During data collection, information on the existing cooling systems were collected, and potential steam adsorption chiller technologies were identified. In system analysis, the existing cooling system was compared to a hypothetical configuration that incorporated the identified steam adsorption chiller technology. In cost analysis, the team evaluated the life-cycle cost (LCC) associated with the steam adsorption chiller technology.

# 2 A Comparative Analysis: Conventional Chillers vs. Adsorption Chillers

Conventional Chillers, often relying on vapor compression refrigeration technology, have been the workhorses of cooling systems for decades. These systems efficiently provide cooling through the phase-change process of refrigerant gases, making them a staple in various industrial and commercial settings. They are well-established, widely used, and typically known for their reliability. However, they are not without their limitations.

Adsorption Chillers, on the other hand, represent a departure from the conventional. These innovative systems operate on the principle of adsorption, wherein a solid adsorbent material effectively captures and releases a refrigerant vapor during a cyclic process. This departure from the vapor compression cycle comes with several noteworthy advantages.

**Energy Efficiency:** Adsorption chillers have the potential to be highly energy-efficient, particularly when powered by low-grade heat sources such as waste heat or solar energy. This makes them a compelling option for organizations aiming to reduce their carbon footprint and energy consumption.

**Environmental Friendliness:** Adsorption chillers typically employ environmentally friendly refrigerants, avoiding the use of compounds known to contribute to ozone depletion or global warming. This aligns with sustainability goals and regulatory requirements.

**Reduced Noise Levels:** Unlike conventional chillers, which can be noisy due to the operation of compressors and fans, adsorption chillers operate quietly. This makes them suitable for settings where noise pollution is a concern, such as residential areas or noise-sensitive industrial facilities.

**Corrosion Resistance:** Adsorption chillers can be less susceptible to corrosion issues often associated with conventional systems, particularly in environments with aggressive chemicals or high humidity.

**Flexibility in Heat Sources:** Adsorption chillers can utilize a variety of heat sources, including waste heat, solar thermal energy, or natural gas, offering versatility in their applications.

However, it's important to acknowledge that adsorption chillers are not a one-size-fits-all solution. They may have limitations in terms of cooling capacity compared to large-scale conventional chillers. Additionally, their upfront costs can vary significantly depending on the specific system requirements and installation factors, as previously mentioned.

To facilitate the decision-making process, this study turns its focus toward the Lake City Army Ammunition Plant (LCAAP) in Independence, Missouri. In initial discussions with LCAAP stakeholders, it became apparent that their existing chiller systems presented a prime opportunity for improvement. In alignment with LCAAP's forward-looking Area Development Plan, our research aims to compile and distill the numerous benefits associated with the introduction of adsorption chillers within the distinctive operational context of this facility. Table 1 shows key aspects when selecting the most appropriate chiller for specific operations.

Table 1. Conventional and adsorption chillers comparison.

| Comparison Aspects | Conventional Chillers | Adsorption Chillers |
|---|---|---|
| Operation Process | Mechanical compression to circulate a refrigerant through a cycle (phase changes) to achieve cooling | Thermodynamic process, adsorption of a refrigerant vapor into an absorbent material. Heat desorbs the refrigerant to achieve cooling. |
| Energy Source | Electricity and natural gas | Hot water, solar energy, and waste heat |
| Efficiency | Highly efficient when operating under design capacity. Efficiency issues at part load conditions. | Efficiency varies as the heat source varies. |
| Environmental Impact | Refrigerants can be harmful to the environment. Noise pollution from compressors. | Reduces environmental impact by using waste heat, and it can also be operated with environmentally friendly refrigerants. |
| Maintenance | Several moving parts that require maintenance, such as compressors. | Less moving parts requiring maintenance. |
| Footprint | Can be sized depending on the application but still bigger than adsorption chillers. | Appropriate for limited spaces and less heavy than conventional chillers. |
| Load | Designed for specific load conditions. Full load operation can impact its wear and tear. | Efficient at part-load conditions, more flexible designs. |
| Initial Investment | Lower investment cost. | Initial cost is usually high due to the purchase of adsorbent materials. |

Besides the components shown in Table 1, Table 2 displays a compilation of commercially available adsorption chillers compared to the chillers currently in use at the site describe in Section 3.

Table 2. Commercially available chillers comparison.

| Equipment details | Description (Series) | Bry-Air (adsorption chiller (ADC) Series C-Frame | | | | ADC Series D-Frame | | | ADC Series E-Frame | | | | ADC Series -Ext. E-Frame | ADC Series F-Frame | | | | York Centrifugal Chiller |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Design (Model) | C-40 | C-30 | C-20 | C-10 | D-75 | D-60 | D-50 | E-150 | E-140 | E-120 | E-100 | E-190 | F-330 | F-300 | F-250 | F-200 | York Model YCWL0157HE |
| | Capacity (Tonnes) | 41 | 30 | 20 | 10 | 76 | 61 | 51 | 152 | 142 | 124 | 104 | 190 | 335 | 305 | 254 | 203 | 151.1 |
| Heat Source | Water | | | | | | | | | | | | | | | | | |
| Evaporator Data | Inlet Temperature (°C) | 12.8 | 12.8 | 12.8 | 12.8 | 12.8 | 12.8 | 12.8 | 12.8 | 12.8 | 12.8 | 12.8 | 12.8 | 12.8 | 12.8 | 12.8 | 12.8 | 12.8 |
| | Outlet Temperature (°C) | 7.2 | 7.2 | 7.2 | 7.2 | 7.2 | 7.2 | 7.2 | 7.2 | 7.2 | 7.2 | 7.2 | 7.2 | 7.2 | 7.2 | 7.2 | 7.2 | 7.2 |
| | Flow Rate (l/min) | 371 | 273 | 182 | 91 | 689 | 553 | 462 | 1,382 | 1,291 | 1,128 | 946 | 1,726 | 3,043 | 2,771 | 2,309 | 1,843 | 362.3 |
| | Pressure Drop (meters [mtr.] $H_2O$) | 8.5 | 5.8 | 3.4 | 1.2 | 8.5 | 6.4 | 5.2 | 9.1 | 8.2 | 7 | 5.5 | 10.7 | 8.8 | 7.9 | 6.1 | 4.6 | 3.6 |
| | Connection Size (mm) | 65 | 65 | 65 | 65 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 200 | 200 | 200 | 200 | Unknown |
| Condenser Water | Inlet Temperature (°C) | 29 | 29 | 29 | 29 | 29 | 29 | 29 | 29 | 29 | 29 | 29 | 29 | 29 | 29 | 29 | 29 | 29 |
| | Outlet Temperature (°C) | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 |

Table 2 (cont.). Commercially available chillers comparison.

| | Description (Series) | Bry-Air ADC Series C-Frame | | | | ADC Series D-Frame | | | ADC Series E-Frame | | | | ADC Series -Ext E-Frame | ADC Series F-Frame | | | | York Centrifugal Chiller |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| — | Flow Rate (l/min) | 1,120 | 821 | 549 | 273 | 2,078 | 1,669 | 1,397 | 4,164 | 3,887 | 3,395 | 2,846 | 5,201 | 9,167 | 8,346 | 6,949 | 5,556 | Not applicable (N/A) |
| | Pressure Drop (mtr. $H_2O$) | 11.9 | 7.9 | 4.6 | 1.8 | 11.9 | 8.8 | 7.0 | 13.7 | 12.5 | 10.7 | 8.2 | 13.7 | 12.8 | 11.3 | 8.8 | 6.7 | N/A |
| | Connection Size (mm) | 100 | 80 | 65 | 65 | 125 | 125 | 125 | 150 | 150 | 150 | 150 | 150 | 250 | 250 | 250 | 250 | N/A |
| Hot Water | Inlet Temperature (°C) | 90.6 | 90.6 | 90.6 | 90.6 | 90.6 | 90.6 | 90.6 | 90.6 | 90.6 | 90.6 | 90.6 | 90.6 | 90.6 | 90.6 | 90.6 | 90.6 | N/A |
| | Outlet Temperature (°C) | 84 | 84 | 84 | 84 | 84 | 84 | 84 | 84 | 84 | 84 | 84 | 84 | 84 | 84 | 84 | 84 | N/A |
| | Flow Rate (l/min) | 621 | 454 | 303 | 151 | 1,151 | 924 | 772 | 2,301 | 2,150 | 1,877 | 1,575 | 2,877 | 5,072 | 4,618 | 3,846 | 3,073 | N/A |
| | Pressure Drop (mtr. $H_2O$) | 4.3 | 2.7 | 1.8 | 0.6 | 4.3 | 3.4 | 2.4 | 6.7 | 6.1 | 5.2 | 4.0 | 9.1 | 6.1 | 5.5 | 4.3 | 3.0 | N/A |
| | Connection Size (mm) | 80 | 65 | 65 | 65 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 200 | 200 | 200 | 200 | N/A |
| **Power** | Operating kW Consumption | 0.6 | | | | 0.8 | | | 0.8 | | | | 0.8 | 1.3 | | | | 159.27 |

# 3 Engineer Research and Development Center's (ERDC) Investigation at Lake City Army Ammunition Plant (LCAAP) in FY23

The Engineer Research and Development Center (ERDC) team submitted a request for information at the beginning of FY23 to gather the available data on current systems at LCAAP. On 21 March 2023, the team engaged with stakeholders and conducted an on-site visit to the facilities housing the existing cooling infrastructure. During this visit, they discovered that the installation already features a cooling plant effectively serving the required areas within the facility. Notably, there is a keen interest in exploring the potential of incorporating adsorption chillers to enhance air conditioning, particularly during the sweltering summer months.

## 3.1 Available System at the Site

LCAAP has a central utility plant called 15B, which was installed in 2016. Building 15B has four large variable speed drive, R134a York centrifugal chillers with a combined capacity of 5,250-ton of cooling with spaces for another chiller, cooling tower cell, and additional chilled water and condenser pumps.[*] The chilled water pumps provide circulation through the chilled water loop, and the condenser pumps provide circulation through the outdoor cooling tower cells. All pumps are variable speed and can controlled from the Johnson Control's building management system (BMS).

The chilled water system provides chilled water to air handlers located in Building 1 and Building 3, which are two large manufacturing buildings. Main factory and office areas are served by the HVAC systems. The HVAC systems provide cooling for worker comfort and productivity and help keep electronics cool in the factory and provide a stable temperature environment while limiting maximum relative humidity. The chilled water system operates about 9 to 10 months out of the year and is shut down in wintertime. The chilled water system does not serve energetic wings and does not directly cool critical processes—separate systems are installed for those needs.

---

[*] LCAAP Installation Energy and Water Plan (2020); internal use report.

LCAAP also includes Building 15, which houses the large central steam generation facility. The current system has six boilers (three large 1940s vintage Babcock & Wilcox boilers, one 1970s vintage Nebraska boiler with flue gas economizer), and one small Superior boiler. Maximum steam demand is currently in the range of 115,000 lb/hr.* Steam is generated year-round, since it serves critical processes and provides humidification for energetic process areas.

A new cogeneration plant is planned in the future (currently in design stage) to be able to meet the steam demand of the facility, while providing electricity to the plant. The plant is schedule to be online in approximately four years.

The year-round availability of steam, both presently and in the future, makes the installation of a steam-fed adsorption chiller a compelling choice. This can significantly reduce electrical demand during the summer months. In conjunction with this installation, a new cooling tower cell, chiller, and condenser water pumps, complemented by variable frequency drives (VFD), would be incorporated.

Adsorption chillers offer advantages of reliability, ease of operation, and a compact footprint, which aligns well with the available space in B15B. Adding the additional chiller also improves redundancy, as currently all four installed chillers run in extremely hot weather. This improves resiliency and flexibility for the plant.

Given the focus on steam adsorption chillers, as opposed to double-effect absorption chillers, and with the possibility that adsorption chillers may offer similar or even smaller footprints compared to centrifugal chillers, the facilities engineering team at Lake City thinks it's worth considering a high-capacity adsorption chiller, provided that the associated payback is favorable. The existing chillers have a nominal capacity of 1,312 tons.

Adsorption chillers offer an environmentally friendly and energy-efficient cooling solution for facilities. These chillers employ an adsorption process in which water vapor is absorbed by a desiccant material, eliminating the

---

* For a full list of the spelled-out forms of the units of measure used in this document and their conversions, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office, 2016), 248–52 and 345–47, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

need for mechanical compression and reducing reliance on traditional refrigerants. By using adsorption technology, not only can overall energy costs be significantly reduced, but the environmental impact is also minimized due to the reduced use of refrigerants. Additionally, in cases where excess steam is available from a cogeneration facility, it can be harnessed to produce chilled water using adsorption chillers, reducing the electrical demand from the cogeneration turbines. This not only optimizes energy usage but also aligns with sustainable and eco-friendly practices.

During the site visit it was discussed that steam adsorption is sensible for summer months, as it helps to control the humidity levels in the manufacturing process at LCAAP, which ensures safety. Currently, four chillers are run, instead of two, for this purpose. More chillers are preferred to reduce the horsepower.

The stakeholders also mentioned that a 1-mill-gal tank is needed for chill water storage, and they would like adsorption chillers at a new facility being built, but it is too far. It is also desired to have a steam turbine driver.

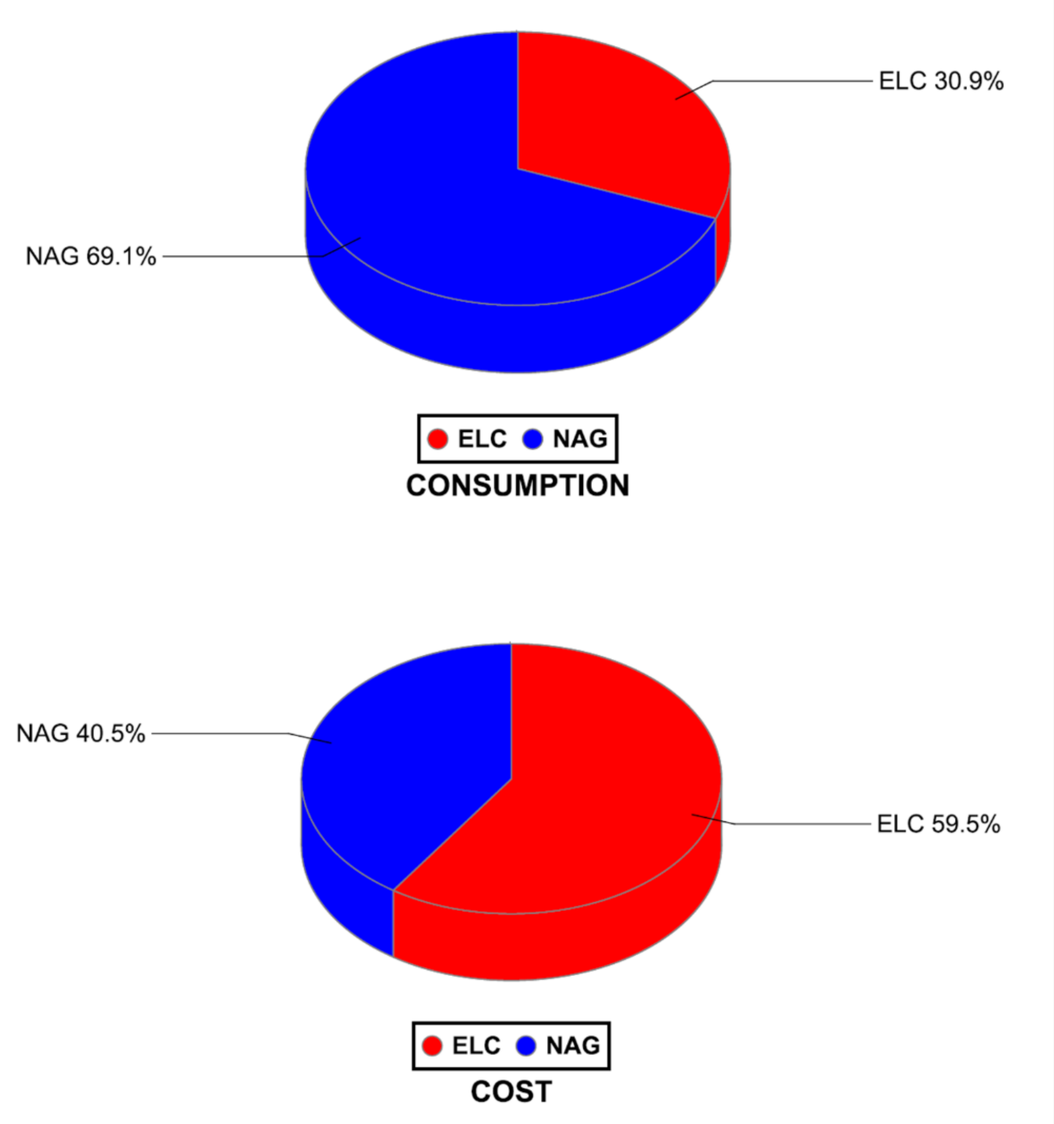
LCAAP is planning for the construction of a central utility plant, which could be a great opportunity to add and replace existing conventional with adsorption chillers. The cooling standards in Missouri are established by the Missouri Department of Natural Resources and are based on the International Energy Conservation Code and ASHRAE standards (https://oa.mo.gov).

## 3.2 Current Energy Consumption

Energy consumption at LCAAP consist of electricity and natural gas. Figure 2 shows the energy consumed in 2021, while Figure 3 shows historical energy consumption and cost on the fourth quarter of each fiscal year. The trend shows that cost and consumption were steady with a small jump in 2016, this could be due to the increased energy to operate the cooling equipment. No major changes were identified between 2016 and 2019, but the consumption was lower in 2020, this could be because of stay at home restrictions. It is unknown why the cost jump in FY22; however, it is usually due to delays in billing. Often, the site is not billed until the last quarter. Section 3.1 describes energy cost.

Figure 4 shows the energy consumption and its cost (based on rates described in Table 3) per chillers. As expected, the consumption is much higher during the summer months. During the fall, chiller 3 takes most of the load.

Figure 2. Energy distribution and cost in 2021.



*NAG (Natural Gas) and ELC (Electricity).

Figure 3. Energy consumption and cost reported on the last quarter since FY13.

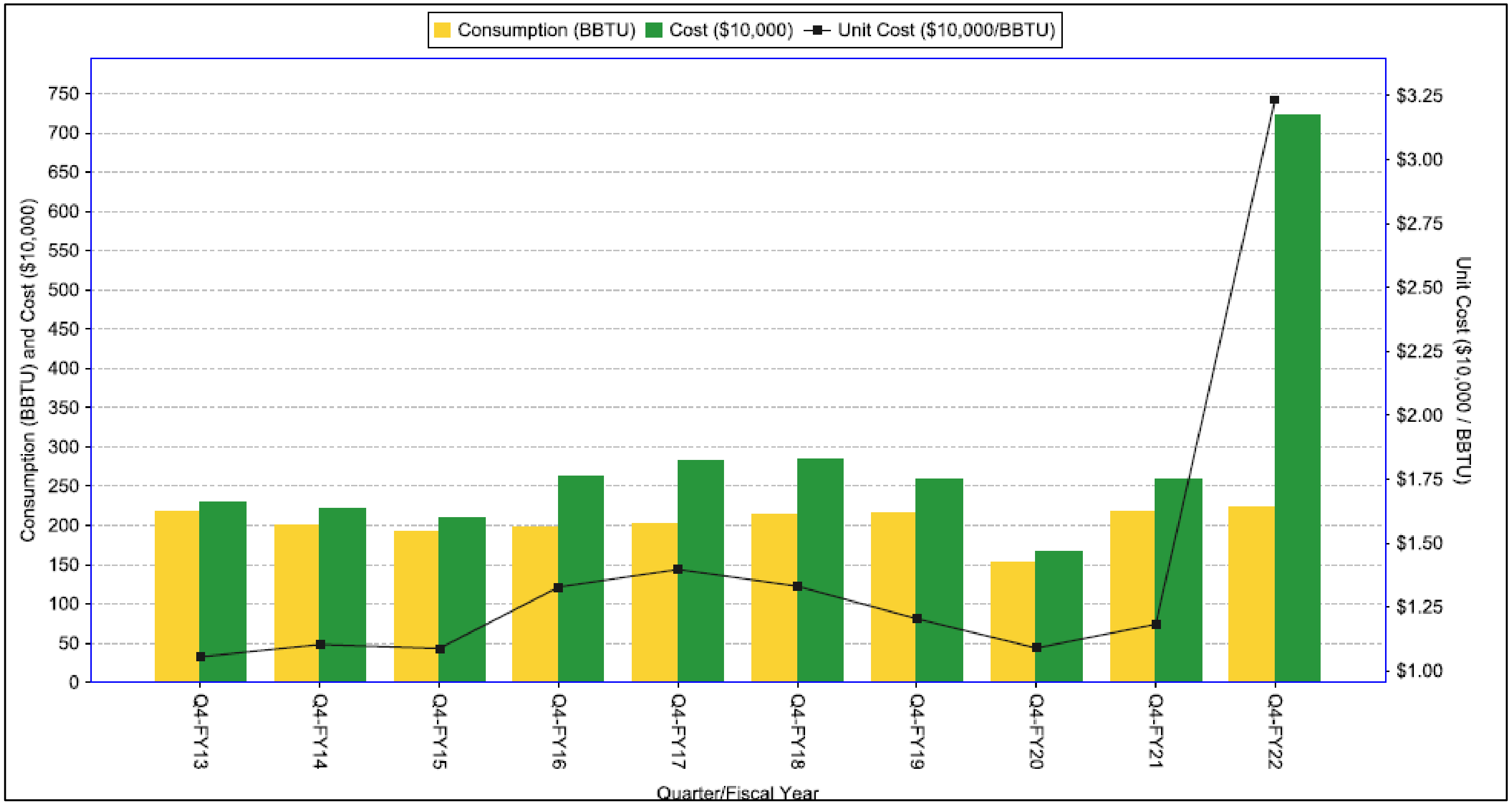
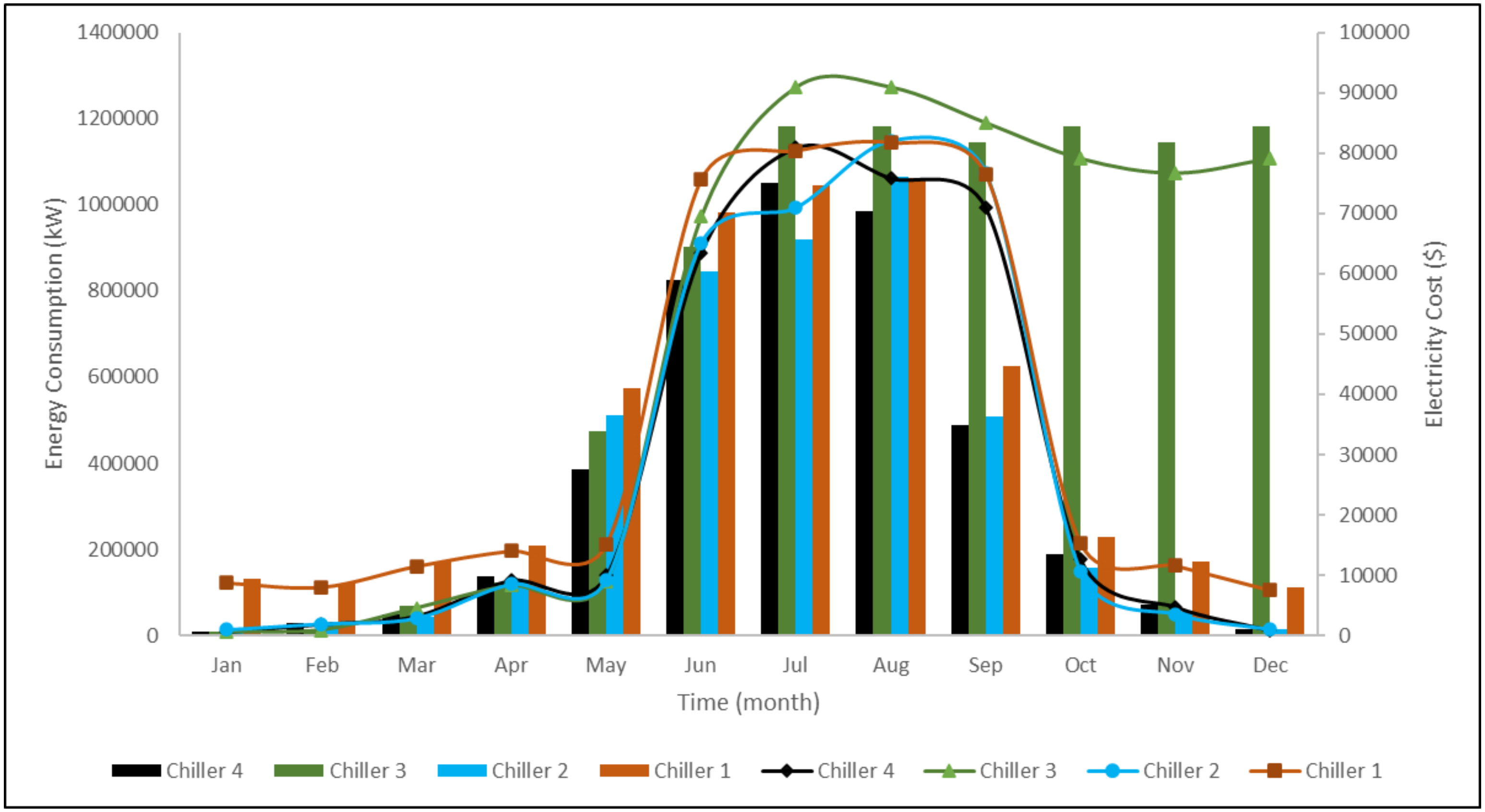


Figure 4. Energy consumption and cost per chiller at Lake City Army Ammunition Plant (LCAAP).



The energy rates at the site vary slightly throughout the year. As shown in Table 3, the electric cost and gas cost are higher during the summer, while the water cost is the same throughout the year.

Table 3. Utility rates at Lake City Army Ammunition Plant (LCAAP).

| Utility | Rate | Month |
|---|---|---|
| Electric blended | \$0.077/kWh | Mid-May through mid-September |
| Electric blended | \$0.067/kWh | Mid-September through mid-May |
| Gas | \$0.00862/ft$^3$ | April through October |
| Gas | \$0.00844/ft$^3$ | November through March |
| Water | \$0.562195/kgal | — |

## 3.3 Potential for Adsorption Chillers

The ERDC’s evaluation of LCAAP has unveiled promising opportunities for advancing the facility's cooling infrastructure and enhancing energy efficiency. Adsorption chillers emerge as a particularly favorable solution, given their ability to efficiently utilize surplus steam and reduce dependence on electrical cooling systems, aligning perfectly with sustainability objectives.

LCAAP’s upcoming construction plans for a central utility plant present an ideal opportunity to seamlessly integrate adsorption chillers into the infrastructure while gradually phasing out conventional systems. Looking ahead, considerations such as the incorporation of steam turbine drivers and alignment with Missouri's cooling standards are pivotal elements of the strategic roadmap. These comprehensive efforts converge toward a future in which adsorption chillers not only optimize cooling operations but also underscore LCAAP’s commitment to sustainability, resilience, and cost-effectiveness.

Furthermore, to facilitate informed decision-making, an example cost analysis related to steam adsorption chiller technology is provided in the Cost Analysis section of this report. This analysis serves as a valuable reference for assessing the economic viability of implementing this innovative cooling solution.

# 4 Cost Analysis

## 4.1 Cost Analysis of Adsorption Chiller compared to Absorption Chiller

The life cycle cost analysis for the inclusion of adsorption chillers at any facility considers costs related to procurement and installation, operation and maintenance (which includes the energy consumption and annual maintenance), and disposal costs at the end of life. Additional costs may include training for personnel to operate and maintain the equipment. Other cost considerations may include design, shipping and transportation, configuration (e.g., connecting to existing control interfaces) costs, and end-of-life disposal costs of the existing asset if a replacement, or the installed unit (when replaced in the future).

In this subsection, the cost analysis does not apply to a specific garrison or installation, but instead proposes a basic cost analysis for an adsorption chiller. Due to the generic application, the analysis does not consider specific sizing requirements for chilling capacity at a facility, any location specific requirements or factors for specified use (e.g., paint facility versus administrative office space), or any modifications required to integrate into the existing infrastructure.

In this cost analysis, several key assumptions have been made:

1. **Leveraging Bry-Air data—**Given the absence of US manufacturer data for adsorption chillers, this analysis relies on technical specifications obtained from Bry-Air Adsorption Chillers (Bry-Air 2015). Specifically, it assumes that the unit purchased aligns with the technical specifications of the model D-75 with a regeneration temperature (RT) of 76 (Bry-Air 2015), chosen due to its similarity to the RT capacity used in a relevant case study (Hansen et al. 2013). Additional assumptions based on Bry-Air's technical specifications include a minimum service life of 20 years, no need for periodic maintenance, and the use of Special Silica Gel (Inert)-S2 as the desiccant.
2. **Cost estimation—**Building upon a prior case study (Hansen et al. 2013), this analysis assumes the cost for an adsorption chiller to be $784,039.00. This figure is derived by subtracting costs associated with solar cooling racks, resulting in an adjusted amount of $560,028.00. This cost has been adjusted for inflation, assuming an approximate 40% increase since 2013.

Additionally, the analysis assumes that the annual average maintenance cost difference between adsorption chillers and absorption chillers is approximately $8,792.00, adjusted according to the inflation rate.

3. **Existing chiller system energy costs—**The energy costs for the existing chiller systems are estimated at $36,202.70 for the May through August timeframe in the first year, with the assumption that these costs adjust in accordance with the inflation rate.
4. **Steam source and maintenance costs—**It is assumed that the steam source is co-located near the chiller location, incurring negligible connection costs. Furthermore, adsorption chiller maintenance costs are deemed negligible due to the minimal maintenance requirements stipulated in the technical specifications.

Additionally, the following operating conditions are assumed:

**Energy efficiency—**Adsorption chillers are presumed to have fewer moving parts and to consume approximately 10% of the electricity compared to typical absorption electric chillers (benefit) (Hansen et al. 2013). Therefore, energy costs are calculated as 10% of the energy consumption of absorption chillers.

**Salvage value and disposal costs—**It is assumed that there is no salvage value or disposal costs associated with this analysis.

**Operating hours—**The adsorption chiller is expected to operate continuously, 24 hours a day, 7 days a week, during the months of May through August, aligning with the energy consumption data mentioned earlier.

**Energy rates—**Electrical energy costs are assumed to be sourced from the same provider as the energy costs mentioned earlier, with energy rates remaining constant at the last reported amount.

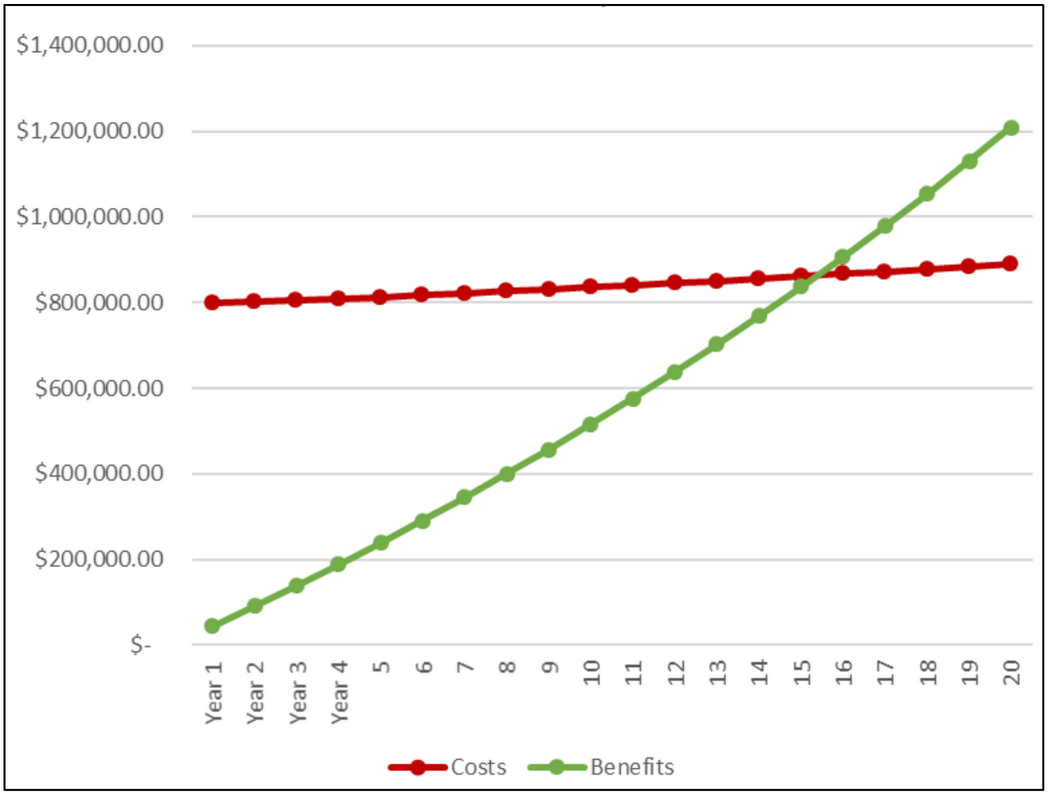
**Training costs—**Minimal training costs, estimated at $5,000.00 for the first year, are expected for users during the installation of the new adsorption chiller.

**Discount and inflation rates—**A discount rate and inflation rate of 3% are assumed for this analysis.

Figure 5 shows the benefits (*green line*) or cost avoidances (annual operation and maintenance costs associated with traditional chillers) over the lifecycle (20-year period) of the adsorption chiller. Based on this analysis, the payback period for this chiller occurs at approximately 15.5 years. The costs (*red line*) are associated with the initial capital investment, training, and operation and maintenance costs. The benefits are associated with cost avoidances from energy savings and maintenance savings. This cost analysis generated a benefit cost ratio (BCR) of 1.35 to 1. However, when considering a service-related investment such as an adsorption chiller, the least costly alternative or lowest BCR would be the preferred investment to pursue if comparing against different chiller types and specifications.

The initial capital investment for a larger capacity adsorption chiller would have a significant impact on the overall upfront cost. However, the potential for cost savings would mainly stem from reduced energy consumption. For instance, in the case of LCAAP, the ability to accommodate a 1,500-ton adsorption chiller and operate it as a base load system for a significant portion of the year could result in substantial energy efficiency gains.

Figure 5. Cost to benefit—breakeven analysis for adsorption versus absorption chillers.



Again, this analysis considers running a chiller during the hottest months of the year only (May through August), which reflects when the chillers typically would see a high demand of use due to higher external temperatures. Installations that experience prolonged periods of higher external temperatures may result in a different BCR result because the energy costs would extend over additional months. Installations in areas that have lower or higher energy costs may result in a different BCR. The cost estimate for a specific chiller for a specific location would impact the cost analysis. As aforementioned, this study used an estimate from a prior DoD installation due to the lack of available US manufacturers. Changes in energy costs over time would impact the cost savings. Finally, if the rate of inflation over time increases to 5%, the BCR changes to 1.56 to 1 with a breakeven point near the 14 years.

Any site-specific cost analysis efforts would require additional information to add higher fidelity to the initial cost analysis provided. The following factors would need to be considered such as the installation, operational, energy consumption, maintenance, and replacement costs. Specific installation and design efforts would need to be coordinated in order to ensure that the proposed new chiller cooling capacity supports the necessary operations. Additionally, coordination and outages would need to be planned to ensure the continued capability to operate the facility and support installation functions. A utility design cost relates to ensuring the design of the new system provides appropriate input from the steam source to support operations of the adsorption chiller. Other potential costs include the following:

- Construction costs for adsorption chiller site specific set up
    - Interim capability for chilling during construction
    - Plumbing
    - Mechanical
    - Electrical
    - Site preparation
- Actual chiller costs
    - Design fees
    - Monitoring and control units
    - Additional equipment needed

- Procurement cost, vendor installation and delivery
- Labor cost for maintenance

## 4.2 Breakeven Analysis for notional comparison of Adsorption Chiller and LCAAP Centrifugal Chiller

An additional cost analysis was performed to consider a comparison between a centrifugal chiller with a rating of 1310 tons and an adsorption chiller. LCAAP uses centrifugal chiller with rating of 1310 tons capacity. Based on the information summarized in Table 2, there does not currently exist an adsorption chiller with the capacity to match the output of the centrifugal chiller at LCAAP. For example, the largest Bry-Air unit is F-Frame (200–330 tons 12 ft wide × 17.5 ft long × 11.5 ft high, and 46,000 lb) (Bry-Air 2015). This footprint takes up approximately 210SF of floorspace and approximately 12 ft ceiling clearance at a minimum plus considerations for safety and maintenance activities to service the unit.

Because an equivalent unit does not exist, this cost analysis evaluates only upon the potential long-term energy savings and generates a proposed investment cost required in order to break even over the 20-year lifespan of the unit. In this cost analysis, the following key assumptions have been made:

1. **Cost Estimation:** This cost analysis focuses primarily on proposed annual energy savings that may occur if an adsorption system equivalent existed as compared to a centrifugal chiller with 1310 rating. Additionally, the analysis assumes that the annual average maintenance cost for the centrifugal chillers begins at $4,396 and increases annually adjusted according to the inflation rate.

2. **Existing Chiller System Energy Costs:** The energy costs for the existing centrifugal chiller system have an estimated initial year one energy cost of $154,823.20 for a six-month timeframe, with the assumption that these costs adjust in accordance with the inflation rate thereafter.

3. **Maintenance Costs:** Adsorption chiller maintenance costs are deemed negligible due to the minimal maintenance requirements stipulated in the technical specifications for the smaller units.

Additionally, the following operating conditions are assumed:

**Energy Efficiency:** Adsorption chillers are presumed to have fewer moving parts and to consume approximately 10% of the electricity compared to typical absorption electric chillers (benefit) (Hansen et al. 2013). Centrifugal chillers consume half the energy costs of absorption chillers (Wajima et al 2008).

**Salvage Value and Disposal Costs:** It is assumed that there is no salvage value or disposal costs associated with this analysis.

**Operating Hours:** The adsorption chiller is expected to operate continuously, 24 hours a day, 7 days a week, between April and October (6 months) of run time annually.

**Energy Rates:** Electrical energy costs are assumed to be sourced from the same provider as the energy costs mentioned earlier, with energy rates remaining constant through the months of use.

**Training Costs:** Minimal training costs, estimated at $5,000 for the first year, are expected for users during the installation of the new adsorption chiller.

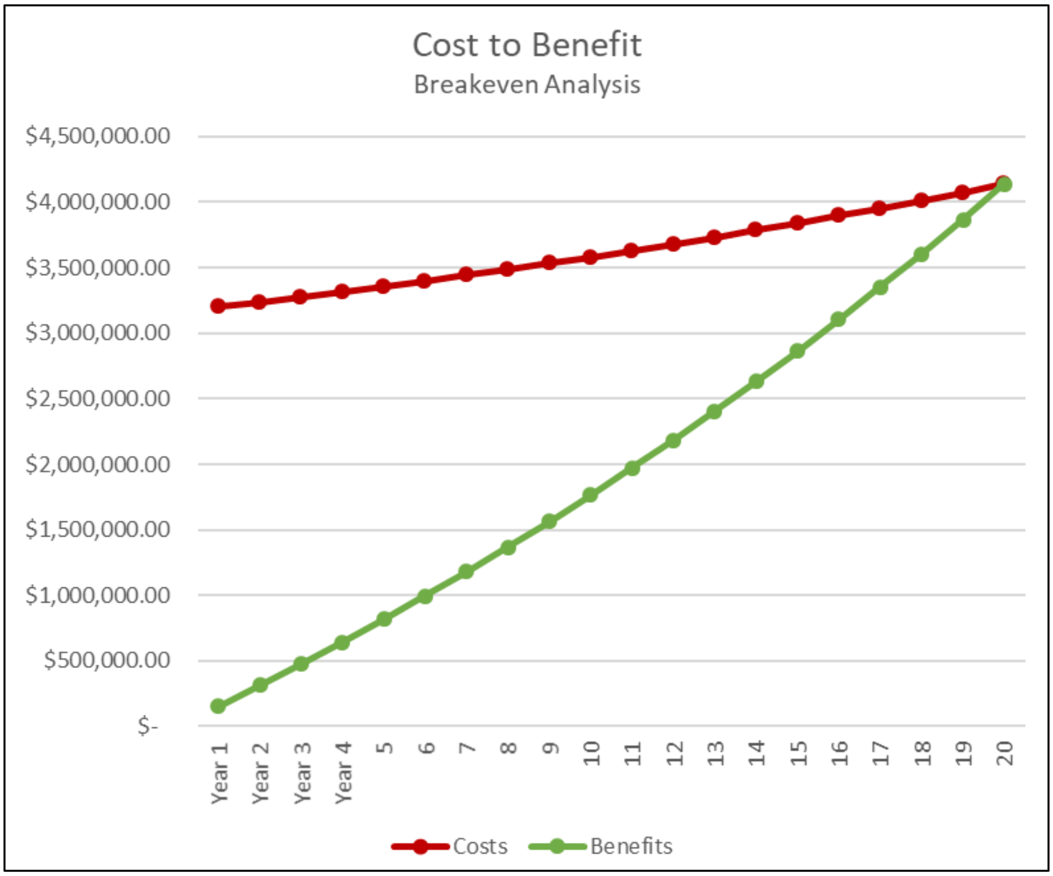
**Discount and Inflation Rates:** A discount rate and inflation rate of 3% are assumed for this analysis.

Based on energy costs savings alone, the theoretical adsorption chiller—if a unit (or combination of units) existed at the capacity required—would theoretically provide a total savings (from energy costs and maintenance costs) of approximately $4.138 M over a 20-year lifetime (given inflation rate of 3% per year).

Any new adsorption chiller(s) and associated setup installation costs would need to have a present-day cost of $3.194 M or less in order to break even with the estimated savings over a 20 year lifetime (given similar assumptions to above) as compared to the existing centrifugal chiller. As a reminder, this initial investment cost would also include the costs to set up the site and connect to the steam source.

Figure 6 shows the benefits (*green line*) or cost avoidances (annual operation and maintenance costs associated with traditional chillers) over the lifecycle (20-year period) of the adsorption chiller as compared to a centrifugal chiller. The costs (*red line*) are associated with the initial capital investment, training, and operation and maintenance costs. The benefits are associated with cost avoidances from energy savings and maintenance savings.

Figure 6. Cost to benefit—breakeven analysis for adsorption versus LCAAP centrifugal chillers.



# 5 Conclusions and Recommendations

## 5.1 Recommendations

Based on the findings of the cost analysis and the broader context of implementing adsorption chillers in facilities, the following recommendations emerge:

**Detailed cost analysis—**Site-specific assessments should include detailed cost analyses that encompass not only the procurement and installation costs but also operational, maintenance, and potential replacement costs. This comprehensive approach ensures a more accurate evaluation of the long-term economic benefits.

**Lifecycle management—**Facilities should adopt a proactive lifecycle management approach for adsorption chillers. This involves regular monitoring, maintenance, and performance assessments to ensure consistent efficiency and cost-effectiveness throughout their service life.

**Flexible design—**When integrating adsorption chillers into existing infrastructure or during new facility design, flexibility is key. Systems should be designed to accommodate potential changes or upgrades in cooling capacity, ensuring adaptability to evolving needs.

**Environmental considerations—**Given the environmental advantages of adsorption chillers, it is advisable to consider their integration as part of a broader sustainability strategy. This includes assessing their potential for reducing greenhouse gas emissions and aligning with sustainability goals.

**Collaboration and knowledge sharing—**Engage with industry experts, manufacturers, and research institutions to stay informed about the latest developments in adsorption chiller technology and best practices. Collaboration and knowledge sharing can lead to ongoing improvements in efficiency and cost-effectiveness.

**Chiller Performance Analysis:** Future research could investigate and validate the cooling output and energy efficiency of adsorption chillers as compared to existing absorption and centrifugal chillers at installations.

## 5.2 Conclusions

In conclusion, the successful implementation of adsorption chillers requires a thoughtful and site-specific approach. By conducting detailed assessments, optimizing energy efficiency, investing in training, and staying attuned to environmental and regulatory considerations, facilities can harness the potential benefits of adsorption chillers while promoting sustainability and cost savings over the long term. The study showed that the use of adsorption chillers presents several advantages over traditional refrigeration systems, including energy efficiency, minimal running costs, easy maintenance, and use of natural refrigerants. The technology is driven by heat, which makes it an ideal solution for clean energy generation. Adsorption chillers can be powered by waste heat or heat generated by solar panels or other devices, eliminating the need for chemical refrigerants and associated maintenance and safety concerns.

Furthermore, the study demonstrated that adsorption chillers could become a viable and environmentally friendly solution for cooling spaces in military installations, particularly when driven by local district heating systems. Although their efficiency may be affected by the season, the benefits of using adsorption chillers outweigh their deficiencies. Additional research demonstrating and evaluating the performance and actual costs of an adsorption chiller could further support these initial findings.

# Bibliography

Bry-Air. 2015. *Adsorption Chiller Technical Data Sheet*. BAA:D0054. Sunbury, OH: Bry-Air. https://www.bryair.com/wp-content/uploads/2020/09/adc-technical-specs.pdf.

Freni, A., G. Maggio, A. Sapienza, A. Frazzica, G. Restuccia, and S. Vasta. 2016. “Comparative Analysis of Promising Adsorbent/Adsorbate Pairs for Adsorptive Heat Pumping, Air Conditioning and Refrigeration.” *Applied Thermal Engineering* 104: 85–95. https://doi.org/10.1016/j.applthermaleng.2016.05.036.

Gado, M. G., S. Ookawara, S. Nada, and I. I. El-Sharkawy. 2021. “Hybrid Sorption-Vapor Compression Cooling Systems: A Comprehensive Overview.” *Renewable and Sustainable Energy Reviews* 143: 110912. https://doi.org/10.1016/j.rser.2021.110912.

Goyal, P., P. Baredar, A. Mittal, and A. Siddiqui. 2016. “Adsorption Refrigeration Technology – An Overview of Theory and Its Solar Energy Applications.” *Renewable and Sustainable Energy Reviews* 53: 1389–1410. https://doi.org/10.1016/j.rser.2015.09.027.

Hansen, T., E. Ringler, and W. Chatterton. 2013. *Demonstration of a Solar Thermal Combined Heating, Cooling and Hot Water System Utilizing an Adsorption Chiller for DoD Installations*. ESTCP Project EW-200928. Birmingham, AL: Southern Research Institute. https://apps.dtic.mil/sti/pdfs/ADA608953.pdf.

Wajima, K., Y. Shirakata, M. Matsuo, K. Ueda, M. Ishikawa, and J. Koga. 2008. “Centrifugal Chiller Maximizing Year-Round Efficiency.” *Mitsubishi Heavy Industries Technical Review* 45 (2): 32–36. https://www.mhi.co.jp/technology/review/pdf/e452/e452032.pdf.

# Abbreviations

| | |
|---|---|
| ADC | Adsorption chiller |
| BCR | Benefit cost ratio |
| CEP | Central energy plant |
| ERDC | US Army Engineer Research and Development Center |
| LCAAP | Lake City Army Ammunition Plant |
| LCC | Life-cycle cost |
| N/A | Not applicable |
| RT | Regeneration temperature |
| VFD | Variable frequency drive |

# REPORT DOCUMENTATION PAGE

| | | | |
|---|---|---|---|
| **1. REPORT DATE**<br>November 2023 | **2. REPORT TYPE**<br>Final Report | **3. DATES COVERED**<br>**START DATE**<br>FY22 | **END DATE**<br>FY23 |

**4. TITLE AND SUBTITLE**
Investigation of Steam Adsorption Chillers to Modernize Existing Central Steam Plant Systems

| | | |
|---|---|---|
| **5a. CONTRACT NUMBER** | **5b. GRANT NUMBER** | **5c. PROGRAM ELEMENT** |
| **5d. PROJECT NUMBER** | **5e. TASK NUMBER** | **5f. WORK UNIT NUMBER** |

**6. AUTHOR(S)**
Melisa Nallar, Shelia K. Barnett, Edith L. Martinez-Guerra, Jamie T. Potter, and Christina H. Rinaudo

| | |
|---|---|
| **7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**<br>US Army Engineer Research and Development Center (ERDC)<br>Cold Regions Research and Engineering Laboratory (CRREL)<br>72 Lyme Road<br>Hanover, NH 03755-1290 | **8. PERFORMING ORGANIZATION REPORT NUMBER**<br>ERDC TR-23-25 |

| | | |
|---|---|---|
| **9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**<br>Deputy Chief of Staff, G9<br>Installation Technology Transition Program (ITTP)<br>Army ACSIM Management Support Office<br>600 Army Pentagon<br>Washington, DC 20310-0600 | **10. SPONSOR/MONITOR'S ACRONYM(S)**<br>ITTP | **11. SPONSOR/MONITOR'S REPORT NUMBER(S)** |

**12. DISTRIBUTION/AVAILABILITY STATEMENT**
Distribution Statement A. Approved for public release: distribution is unlimited.

**13. SUPPLEMENTARY NOTES**
MIPR 11681657

**14. ABSTRACT**

This report investigates the integration of steam adsorption chillers as a modernization strategy for conventional central steam plant systems. Our objective is to assess the feasibility, advantages, and challenges of incorporating steam adsorption chillers into existing steam plant setups to enhance energy efficiency and cooling capabilities. Central steam plant systems have historically been used for steam-based heating but often lack cooling capabilities, necessitating additional cooling infrastructure. Steam adsorption chillers offer a potential solution by using waste steam for cooling, optimizing energy utilization and reducing reliance on traditional cooling methods. Through a comprehensive analysis, this report evaluates the technical compatibility and potential cost implications of implementing steam adsorption chillers. It explores factors such as system integration, operational dynamics, and maintenance requirements to provide a holistic view of the feasibility and benefits of this modernization approach. The findings aim to offer valuable insights to decision-makers and Army facility managers seeking innovative ways to upgrade central steam plant systems. By considering the technical and economic aspects of adopting steam adsorption chillers, this report contributes to the knowledge base for sustainable and efficient energy utilization in central plant operations.

**15. SUBJECT TERMS**
Central steam plant; Chiller technology; Cooling solutions; Energy efficiency; Energy savings; Steam adsorption chillers; Steam-Base, cooling systems; Steam-Based HVAC

| | | | | |
|---|---|---|---|---|
| **16. SECURITY CLASSIFICATION OF:** | | | **17. LIMITATION OF ABSTRACT** | **18. NUMBER OF PAGES** |
| **a. REPORT**<br>Unclassified | **b. ABSTRACT**<br>Unclassified | **C. THIS PAGE**<br>Unclassified | SAR | 34 |

| | |
|---|---|
| **19a. NAME OF RESPONSIBLE PERSON**<br>Melisa Nallar | **19b. TELEPHONE NUMBER (include area code)**<br>(603) 646-4264 |

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) (concluded)**

US Army Engineer Research and Development Center (ERDC)
Information Technology Laboratory (ITL)
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

US Army Engineer Research and Development Center (ERDC)
Environmental Laboratory (EL)
3909 Halls Ferry Road
Vicksburg, MS 39180-6199