HEAT PUMPING USING COMBINED HEAT AND POWER TECHNOLOGY

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ABSTRACT

The United States Department of Energy (DOE) has worked with partners from the gas heating and cooling industry and the power generation industry to improve energy efficiency using advanced absorption technologies, to eliminate chlorofluorocarbons (CFCs) and hyrochlorofluorocarbons (HCFCs), to reduce global warming through more efficient use of primary energy, and to reduce electric peak demand due to air conditioning loads. Key activities include ammonia-based residential and light commercial gas absorption heat pumps and chillers, advanced "hi-cool" heat pump technology, water-based large commercial chillers, and integrated energy systems that match heat driven absorption technology with power generation. Opportunities for further advancements in absorption technologies exist, particularly for expanding integration of energy systems through combined cooling, heating and power applications achieving energy efficiency approaching 80%.

1. INTRODUCTION

Thermally activated heating and cooling systems offer many benefits to consumers, utilities, and the regional and global environment. For end users, they offer energy efficiency and attractive economic payback. For utilities, they offer alternatives to reduce peak electric demand and improve fuel use through integrated resource planning and demand-side management, with benefits for both gas and electric utilities. Additionally, this technology eliminates the use of ozone-depleting chlorofluorocarbon (CFC) and hydrochlorofluorocarbon (HCFC) refrigerants and, when compared to coal, reduces emission of oxides of sulfur, nitrogen and carbon resulting in significant environmental benefits.

The Department of Energy (DOE) supports private-sector efforts to develop thermally activated heating and cooling technologies through its Thermally Activated Heat Pump Program. Oak Ridge National Laboratory (ORNL) manages this program for DOE.

2. RESIDENTIAL AND LIGHT COMMERCIAL GAX ABSORPTION HEAT PUMP

DOE's **G**enerator-**A**bsorber heat e**X**change (GAX) concept, originally described by Altenkirch in 1913, was not put into practice until the early 1980s. Altenkirch showed a generator and absorber operating with overlapping temperatures. An energy-recovery heat-exchange loop between the generator and absorber raises the thermal efficiency by recovering the heat energy released through an exothermic reaction when the ammonia refrigerant mixes with water in the absorber. Although the GAX is a simple thermodynamic concept, it is exceptionally difficult to achieve in compact hardware. Thermal gradients are "upside-down" (in terms of gravity) and a mismatch exists in the heat quantities between the absorber and generator.

Between 1981 and 1996, DOE sponsored development of the basic GAX technology for residential and small commercial applications under an ORNL-directed subcontract with Phillips Engineering. Although others had tried before, Phillips Engineering was the first to build and successfully test the complete GAX cycle in a laboratory prototype in 1984-1985 [1]. This prototype demonstrated significant efficiency improvement, having a heating coefficient of performance (COP) of 1.6 to 1.8 (including flue losses from the gas burner, but excluding electric parasitic losses) and a cooling COP of 0.7 to 0.9.[1] The GAX absorption heat pump COP is 40-80% more efficient than the efficiency of gas furnaces and boilers (see Figure 1).

The DOE program developed proof-of-principle packaged prototypes. In 1993, two GAX absorption sealed systems and one complete GAX heat pump developed by Phillips Engineering were delivered to a major manufacturer for independent testing and evaluation resulting in confirmation of the GAX proof-of-principle. Cost and market studies were conducted to assess commercial feasibility and business opportunities. It was concluded that the GAX technology could become a significant mainstream product in the United States and worldwide. However, it was found to be difficult to work with existing large HVAC manufacturers in a major cost-shared development effort to produce a final product in the face of internal competing products (such as gas furnaces and electric heat pumps and air-conditioners). For these reasons, several different approaches to bringing GAX technology to market are being pursued in the United States. These new approaches involves three separate organizations: Robur, Ambian and Cooling Technologies, Inc.

In 1991, the Robur Group, an Italian Company founded in 1956, acquired the Servel ammonia-water gas air conditioning division product line and manufacturing facility in the United [R-1}. Those Servel products were the same low-efficiency AHE cycle products that had been manufactured for decades. In 1999, Robur Corporation introduced higher efficiency Servel Chillers utilizing GAX absorption technology. This improved absorption cycle has been certified by AGA and UL and has a 0.62 COP, giving a 30% increase in performance over the previous older technology Servel gas absorption products. Today, Robur offers for sale both 3-ton and 5-ton versions of the

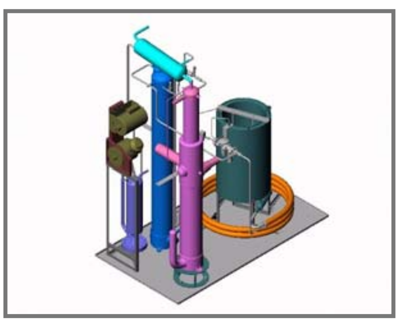
[1] COPs are based on the high heat content of the natural gas.

high-efficiency Servel products, along with 10, 15, 20, and 25-ton "chiller-links" and chiller-heaters using the GAX technology.

A new company named Cooling Technologies, Inc. has been formed to develop and manufacture GAX chillers [CT-1]. Their initial product is a 5-ton chiller with a 0.68 COP. Their unit uses proprietary heat exchangers, a multi-speed condenser fan for high-ambient operation, and a low emissions power burner. A small number of test units are being fabricated for sale in 2002.

In 1998, The Department of Energy and a consortium of gas utilities announced plans to commercialize GAX technology for high efficiency gas-fired heating and cooling units for consumers nationwide. This new company is named Ambian and is owned by several major gas utilities and pipeline companies, including Mississippi Valley Gas, Southern California Gas, Southern Natural Gas, Southwest Gas, and Williams South Central. Manufacturing partners include ITT, a Major U.S. Industrial Corporation; Goettl Air Conditioning, and Dectron Internationale. The Ambian GAX heat pump is expected to increase the efficiency of new gas heating and cooling units by 40 percent over the old Servel technology. [A-1]

Key features for the planned Ambian products include a COP of .70 at ARI rating conditions (95º F), a heating cycle with a COP of 1.4 at ARI rating conditions (47º F), multi-temperature capability for zoning, high part-load efficiencies and high peak-load efficiencies compared to existing products. Planned products include 5-Ton Chillers, 5-Ton Chiller Heaters, 3-Ton Chillers, 3-Ton Chiller Heaters, 5-Ton Heat Pumps, and 3-Ton Heat Pumps. Product introductions are planned to start in 2003 with the complete product line planned by 2005. Currently, 10 Alpha prototype 5-ton chiller units are under test, and a larger number of Beta field-test units are scheduled to be completed in 2002. Figures A-1-3 show the Ambian Alpha units.



Absorption Sealed Module

Alpha Prototype Module

5 RT Chiller Prototype

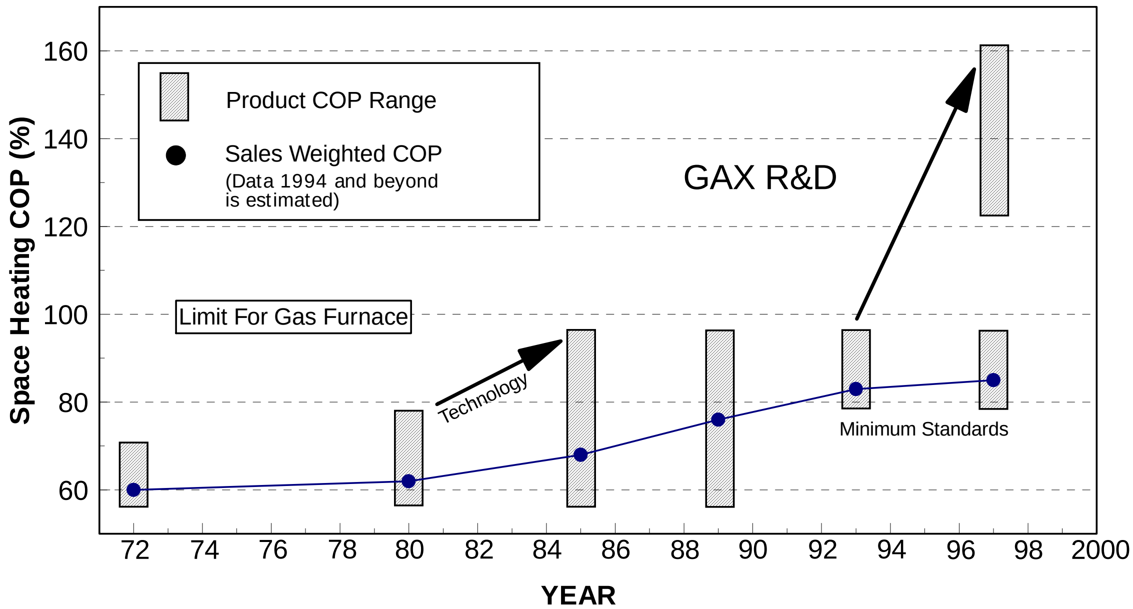


Figure 1. Comparison of heating efficiency of gas furnace and GAX heat pump.

3. HI-COOL HEAT PUMP

The second generation residential and small commercial ammonia-water absorption technology is referred to as “Hi-Cool”. The goal of the Hi-Cool Program is to improve cooling performance by an additional 30 percent when compared to the developmental GAX absorption technology. This translates into performance targets of 1.8-2.0 COPh and 1.0-1.2 COPc.

The potential benefits of hi-cool heat pumps include year-round energy-use reduction and expansion of the market for gas-fired heat pumps, particularly in warmer climate cooling-dominated markets. The Hi-Cool technology is also expected to be good for refrigeration applications.

ORNL managed a competitive procurement and selected multiple subcontractors to develop “Hi-Cool” heat pumps. Battelle/ARCTEK, Energy Concepts, Phillips Engineering, R.A. Technology, Rocky Research, and United Technologies Carrier Corporation conducted heat pump research using fluids and computer models derived from earlier research. These researchers conducted analytical evaluation and selection of best cycle(s) and evaluated critical components needed for prototype development to achieve Hi-Cool goals.

ORNL conducted a technical peer review of the six subcontractors development concepts. Energy Concepts and Rocky Research were selected to continue development by constructing laboratory prototypes for proof-of-principle testing. During 2001-2002, both projects developed and tested laboratory proof-of-principle Hi-Cool prototypes. Energy Concepts Company has developed an eight-ton Hi-Cool laboratory breadboard prototype with a measured gas-fired COP of 0.86 at the 95°F air-cooled rating condition. It also achieves a gas-heating COP of 1.4 at 17°F ambient. [ECC-1] Rocky Research has developed a multi-stage 3-ton ammonia Hi-Cool complex compound solid-vapor sorption cycle heat pump laboratory prototype with similar performance. [RR-1]

4. LARGE COMMERCIAL CHILLER

Another key activity in the DOE Thermally Activated Technology Program is a large commercial triple-effect chiller program, using the LiBr/H_2O fluid pair and operating at higher temperatures and efficiencies than current technology. The goal of DOE's program is to improve cooling efficiency by as much as 40 percent, compared with double-effect absorption chillers currently on the market. The DOE, through ORNL, has been working with the absorption chiller industry to build fully functional triple-effect absorption chillers.

Numerous “triple-efficiency” absorption cycles are theoretically possible and researchers from around the world have proposed many triple-effect cycles [3,4,5,6,7,8,9]. However, only a few of the theoretical triple-effect cycle variations are thought to be potentially commercially practical.

In 1989, the Trane Company started development of a triple-effect cycle concept initially proposed by ORNL/DOE [7]. With support from the Gas Research Institute, Trane (April, 2000) announced that they have had a 375–ton production prototype triple-effect in operation for several years. Their triple-effect is based on currently manufactured “off-the-shelf” double-effect components. Trane has achieved a thermodynamic COP exceeding 1.6 (compared to 1.0 to 1.2 for equivalent technology double-effects), demonstrating more than a 30% increased COP. Their earlier 110-ton triple-effect laboratory prototype is shown in figure T.

Figure T: Trane's Laboratory Prototype Dual-Loop Triple-Effect Chiller

Once the Trane/GRI dual-loop, triple-effect program was underway, DOE and ORNL identify and evaluated promising alternative multiple technologies. A double-condenser coupled (DCC) concept, emerged as the best alternative and was patented by ORNL in 1993 [8]. This cycle was predicted to be more than 30% higher efficiency than equivalent double-effect machines.

The DCC concept, is the base cycle used for the design of the field test unit built by York [8] in a cost-shared program with DOE. Features of the DCC triple-effect chiller include the "generic" addition of a third generator and condenser to the double-effect absorption cycle, plus a new way of coupling the refrigerant from the third condenser with the refrigerant from the second generator. Greater efficiency is achieved by "double-coupling" both the third condenser's refrigerant and the second generator's refrigerant with the first generator.

The York laboratory prototype triple-effect chiller was operated at different loads for approximately 2,400 hours through December 2000 (see Figure Y), with no unusual accumulation of non-condensibles in continuous operation. The COP was close to theoretical predictions of 30% higher efficiency.

Figure Y. Triple effect, exhaust-heat fired absorption chiller tested at York International, York, Pennsylvania.

The final phase of work, construction of a field test triple-effect chiller prototype, factory testing, and a field test demonstration in Clark County, Nevada, is underway and expected to conclude this year. The design goal for this triple-effect chiller is to achieve 400 tons of cooling capacity.

York constructed and tested the direct-fired triple-effect chiller for over 200 hours before shipping the unit to the field test site at the Clark County Government Center [see photo], in Clark County, Nevada, in January 2002. The chiller was installed and will be field-tested during the Summer of 2002 (see Figure Y).

Figure Y. Triple effect, direct fired absorption chiller installed at the Clark County Government Center, Clark County, Nevada.

In 2001, Triple-effect absorption chiller technology was selected for one of the DOE Energy 100 Awards. These awards were given for the top 100 discoveries and innovations in consumer technology coming out of DOE laboratories during the 23-year history of DOE (1977-2000).

5. INTEGRATED ENERGY SYSTEMS—COOLING, HEATING AND POWER

The traditional energy cycle involves the combustion of scarce fossil fuels to generate electricity to power air conditioners and dehumidifiers, ventilation systems, lighting, and a wide variety of household, commercial, and industrial appliances and equipment. More than 50% of the energy content of the fuel is lost at the power plant through the discharge of waste heat into the atmosphere or adjoining lakes, rivers, and streams. Further losses occur in electrical power generation and transmission. On-site and near-site power generation allows waste heat from the turbines, gas-engines, or fuel cells (close to the end-users' thermal loads) to be used as the input power for thermally activated absorption chillers for air-conditioning as well as generating steam and hot water for space heating and other building applications. Making use of what is normally waste heat through Integrated Energy Systems (IES) for Cooling, Heating And Power (CHP) meets the same building electrical and thermal loads with much lower input of fossil fuels yielding very high resource efficiencies.

Integrated Energy Systems can improved energy efficiency from typically 33% (for central power plant generation) to as high as 80%. Success of Integrated Energy Systems technology depends on two key elements: optimizing the recovery of thermal energy from onsite power generation, and cost effective integration of thermal recovery/use systems (such as absorption chillers).

Thermally driven technologies like absorption chiller systems depend on heat and temperature for operation. Therefore, when examining onsite power technologies for IES cooling heating and power combinations with absorption technologies, one must first look toward the temperatures of available recoverable thermal energy streams. Table 1 shows potential matching of various power generating technologies with various absorption chillers:

Power Source	Temp	Matching Technology
Gas Turbine	>1,000 F	Triple-Effect, Double-Effect or Single-Effect
Solid Oxide Fuel Cell	~ 900 F	Triple-Effect, Double-Effect or Single-Effect
Micro-turbine	~ 600 F	Triple-Effect, Double-Effect or Single-Effect
Phosphoric Acid Fuel Cell	~ 250 F	Double-Effect (pre-heat) or Single-Effect
IC Engine	~180 F	Single-Effect
PEM Fuel Cell	~ 140 F	Single-Effect (pre-heat)

Table 1. Integrated Energy Systems Matched to Power Generation and Absorption Technology.

For example, the Trane triple-effect has a 450ºF generator solution temperature, making such a triple-effect potentially a good match to a variety of power-generating turbine and fuel cell technologies for Integrated Energy Systems (cooling, heating and power) applications.

In 2001, Oak Ridge National Laboratory (ORNL) established the Cooling, Heating, and Power Laboratory, located in Oak Ridge, Tennessee. This facility has been designated a National User Facility by the Department of Energy. Companies can use the ORNL CHP Laboratory to augment their own research and development facilities as they work to integrate small power-generation equipment, such as micro-turbines and fuel cells, with absorption cooling equipment and other heat recovery equipment into Integrated Energy Systems for cooling, heating and power applications.

Compared to today's custom engineered IES systems, packaged IES systems should improve performance (efficiency), increase reliability, reduce first (capital plus installation) cost, and reduce maintenance cost. Development of Packaged IES systems will enable true "One-Stop Shopping" for simplified evaluation, specification, bidding and purchasing of IES by many more architects, engineers, developers, and building owners. In early 2001, Oak Ridge National Laboratory issued a request for proposals for the development of First Generation Packaged Cooling, Heating and Power Systems.

In August 2001, U.S. Department of Energy (DOE) Secretary Spencer Abraham announced the First Generation Packaged Cooling, Heating and Power Systems awards. Competitively procured cost-shared subcontracts were negotiated with seven industry teams for research, development, and testing of new, first-generation, packaged. [DOE-1] All seven projects incorporate waste heat driven absorption chillers as a key element utilizing waste heat from power generating equipment. Power generating equipment includes 30, 60, and 70 kW micro-turbines; 300 to 400 kW mini-turbines, 290 kW to 770 kW reciprocating engines, and 2 to 6 MW large turbines. Matching absorption systems range in size from 10-tons to several thousands of tons of cooling capacity and include both single-effect and double-effect cycles. One project also proposes the use of advanced cycle ammonia-water absorption technology for both air-conditioning and refrigeration. The seven industry teams selected for awards are: Honeywell Laboratories, Gas Technology Institute, United Technologies Research Center, Burns & McDonnell, Ingersoll-Rand, NiSource Energy Technologies, and Capstone Turbine Corporation.

6. EDUCATION

DOE supports training and education of students, scientists, and engineers. Two books have been published under DOE co-sponsorship. *Absorption Chillers and Heat Pumps* [16] was written for undergraduate students to introduce them to fluid mixtures, absorption cycles, and absorption equipment. Senior design students may use modeling software (a sample disk is included with the book) to solve the example problems from the text or more difficult classroom problems. *Heat Conversion Systems* [17] was tailored for graduate students in the field of energy conversion, refrigeration, heating and air conditioning, applied physics, and mechanical and chemical engineering. It discusses more advanced systems such as multistage, multi-effect cycles.

7. CONCLUSION

Since the mid 1970’s, absorption technology has largely been sold to niche markets within the United States. By contrast, in Asia, absorption chillers overwhelmingly dominate the large commercial chiller market.

After nearly two decades of research and development, higher efficiency GAX products are entering the marketplace. Advanced absorption technology can offer additional advantages for many applications beyond those achievable with the currently manufactured single-effect and double-effect absorption chiller products. Recently developed triple-effect chillers add significant additional cooling capacity in both direct-fired operation and have demonstrated use of recovered heat for large commercial building applications.

Integrated Energy Systems combine heating, cooling and power technologies to offer significant opportunities for maximizing fuel efficiency with the help of existing or easily modified absorption equipment. Opportunities for further advancements in absorption technologies exist, particularly for expanding integration of energy systems through combined heating, cooling and power applications achieving energy efficiency approaching 80%.

8. ACKNOWLEDGEMENTS

The authors would like to thank the Office of Distributed Energy Resources and the Office of Building Technologies, U.S. Department of Energy, in Washington, D.C. for supporting this work.

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