

HEAT PUMPING USING COMBINED HEAT AND POWER TECHNOLOGY

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ABSTRACT

Since 2001, the United States Department of Energy (DOE) has made a significant shift in focus for development and use of Thermally Activated Heat Pumping Technologies. DOE is working with partners from the heating and cooling industry and the power generation industry to develop Integrate Energy Systems (IES) using advanced thermally driven heat pump technologies for building heating and cooling by recycling otherwise wasted heat from electric generating equipment.

Key activities include heat driven lithium-bromide water absorption chillers matched with power generation to make Integrated Energy Systems (IES); ammonia-based residential and light commercial absorption technology for refrigeration, heat pumps and chillers; and advanced "hi-cool" heat pump technology. Opportunities for further advancements in thermally activated technologies exist, particularly for expanding integration of energy systems through combined cooling, heating and power applications capable of achieving overall energy efficiency approaching or exceeding 80%.

1 INTRODUCTION

Prior to 2001 DOE's Thermally Activated Technologies (TAT) program emphasized stand-alone natural gas fired absorption, adsorption, and desiccant technology equipment development for heating, cooling and dehumidification of buildings.

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 Integrated Energy Systems utilizing thermally activated heating and cooling technologies. Oak Ridge National Laboratory (ORNL) manages this program for DOE.

2 INTEGRATED ENERGY SYSTEMS—COOLING, HEATING AND POWER

The traditional electric power plant 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 electric power plant through the discharge of waste heat into the atmosphere or adjoining lakes, rivers, and streams. Further losses occur in electrical power transmission and distribution. On-site and near-site power generation (distributed generation) allows waste heat from the turbines, internal combustion reciprocating engines, or fuel cells (close to the end-users' thermal loads) to be used as the heat input power for thermally activated absorption chillers for air-conditioning as well as for 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 improve energy efficiency from typically 33% (for central power plant generation) to efficiencies approaching or exceeding 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 using thermally driven heat pumping equipment (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:

**Table 1. Integrated Energy Systems: Matching Power Generation
Waste Heat to Different Absorption Technologies.**

Power Source	Temp	Matching Technology
Gas Turbine	> 500 C	Triple-Effect, Double-Effect or Single-Effect
Solid Oxide Fuel Cell – internal operating temperature	~ 1000 C	Triple-Effect, Double-Effect or Single-Effect
Solid Oxide Fuel Cell – external waste heat rejection temperature	~ 100 C	Single-Effect
Micro-turbine	~ 300 C	Triple-Effect, Double-Effect or Single-Effect
Phosphoric Acid Fuel Cell	~ 100 C	Double-Effect (pre-heat) or Single-Effect
IC Engine – exhaust heat	~ 400 C	Triple-Effect, Double-Effect or Single-Effect
IC Engine – radiator water	~ 80 C	Single-Effect
PEM Fuel Cell	~ 60 C	Single-Effect (pre-heat)

For example, both the Trane and York triple-effect absorption chillers have about a 230°C 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.

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, the U.S. Department of Energy (DOE) 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; 200 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 were: Honeywell Laboratories, Burns & McDonnell, Gas Technology Institute, United Technologies Research Center, Ingersoll-Rand, NiSource, and Capstone Turbine Corporation.

Burns & McDonnell: Burns and McDonnell has teamed with Broad USA, Solar Turbines, and Austin Energy for a 4.5 MW turbine generator integrated with 2,500 RT of direct exhaust fired waste-heat driven absorption chiller (Fig. 1) that has been installed and is operating at the Domain Industrial Park in Austin, Texas. The chiller is one of the first in the world that was designed to be directly fired by the exhaust from a turbine to drive the chiller's generator, rather than use the traditional method of producing steam or hot water to drive the absorption chiller. The IES was commissioned in June, 2004.



Fig. 1. Burns & McDonnell IES in Austin, Texas With a Direct Exhaust Fired Absorption Chiller

Honeywell: Honeywell is teamed with Solar Turbines and Broad, USA for development of larger IES systems. The first system uses a Solar 5 MW turbine generator integrated with a direct exhaust-fired Broad 1000-ton absorption chiller and also with a Heat Recovery Steam Generator (HRSG) that can produce up to 80,000lb/hr of steam. The chiller is also one of the first in the world that was designed to be directly fired by the exhaust from a turbine to drive the chiller's generator, rather than use the traditional method of producing steam or hot water to drive the absorption chiller. The Honeywell IES is installed at the Fort Bragg Army Base in North Carolina. Honeywell is also preparing reference designs for Integrated Energy Systems that span 1.5 to 5.7 MW system configurations. These reference designs will significantly simplify the design and engineering required for future customers.

Gas Technology Institute: The Gas Technology Institute (GTI) teamed with Waukesha, Trane, Ballard Engineering, Charles Equipment, and the University of Illinois to develop Integrated Energy Systems based on internal-combustion reciprocating engine generators ranging from 290 kW to 770 kW in size integrated with absorption chillers. The first prototype system was completed in late 2004 and is now undergoing laboratory testing at GTI.

United Technologies Research Center: After starting separate DOE sponsored IES projects in 2001, United Technologies and Capstone Turbine Corporation formed a strategic alliance in 2003 to continue development of Integrated Energy Systems. The initial system consisted of four 60 kW Micro-turbines coupled with a new direct exhaust heat driven double-effect Carrier absorption chiller. The first product, the PureComfort™ 240 (Fig. 2), entered the market in 2004 and the first commercial system is now operating at a new A&P supermarket in Mt. Kisco, NY. This first commercial installation also includes desiccant dehumidification and hot water recovery as options. Depending on options, the PureComfort™ system has demonstrated 70% to over 80% efficiency, meeting and exceeding DOE's original program goals. The product line has been expanded to include five micro-turbine and six micro-turbine versions (PureComfort™ 300 and PureComfort™ 360).

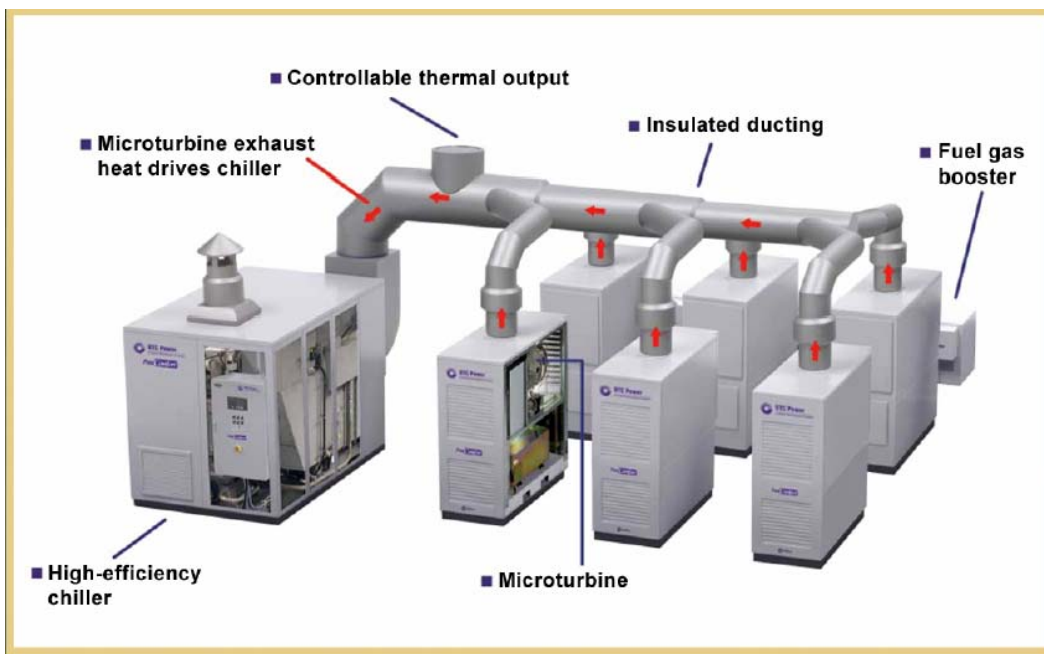


Fig. 2. UTC Power's PureComfort™ System.

NiSource: NiSource developed an Integrated Energy System that used multiple micro-turbines with hot water heat recovery, thermal storage and related control system that was developed specifically for Hotel/Motel applications. The prototype system is in operation at a new Hilton Garden Inn in Chesterton, Indiana.

Ingersoll Rand: The Ingersoll Rand project includes Advanced Mechanical Technologies Inc. (AMTI) and Energy Concepts as partners. Ingersoll Rand manufactures the 70kW micro-turbine that has been integrated with Energy Concept's ammonia-water absorption refrigeration system through an AMTI heat recovery heat exchanger mounted on the micro-turbine's exhaust. The first prototype has been assembled and laboratory tested.

3 RESIDENTIAL AND LIGHT COMMERCIAL GAX ABSORPTION HEAT PUMP

DOE's Generator-Absorber heat eXchange (GAX) concept, which was originally described by Altenkirch in 1913, was not put into actual operating hardware until the early 1980s. Altenkirch showed a generator and absorber operating with overlapping temperatures.

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 Fig. 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 were pursued in the United States with cost-sharing from DOE. These new approaches involve several separate organizations: Robur, and Ambian. An additional company, Cooling Technologies, Inc. with private sector support, has also worked toward developing a GAX product.

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

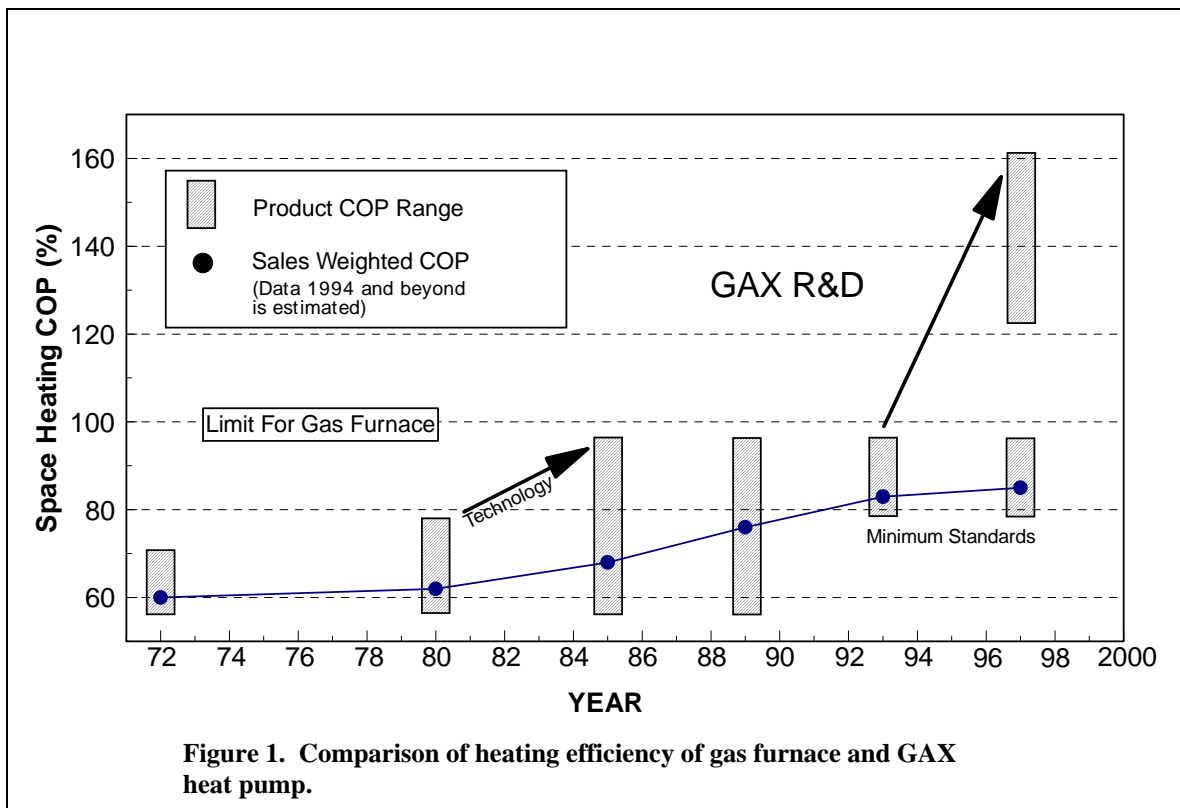
¹ COPs are based on the high heat content of the natural gas.

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 have been fabricated and tested, starting 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. The Ambian GAX heat pump is expected to increase the efficiency of new gas heating and cooling units by 40 percent over the old Serval technology. [A-1]

Key features for the planned Ambian products include a COP of .70 at ARI rating conditions (95° F), a heating cycle with a COP of 1.4 at ARI rating conditions (47° 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. Currently, a number of Beta field-test units are undergoing reliability testing.

Additionally, a waste-heat driven version of the ammonia-water GAX technology for use in Integrated Energy Systems is being planned.



4 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 COP_h and 1.0-1.2 COP_c.

Energy Concepts and Rocky Research were selected for development of laboratory prototypes for proof-of-principle testing. During 2001-2002, both projects developed and tested laboratory proof-of-principle Hi-Cool prototypes. 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] 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]

Energy Concepts has also developed an ammonia-water refrigeration version of their technology specifically designed to be direct fired with turbine exhaust from a micro-turbine for use in Integrated Energy Systems.

5 LARGE COMMERCIAL CHILLER

Another key activity in the DOE Thermally Activated Technology Program that has been completed was a large commercial triple-effect chiller development program, using the LiBr/H₂O 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. DOE has been working with the U.S. absorption chiller industry to build fully functional triple-effect absorption chiller prototypes.

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 Fig. 3.



Fig. 3. Trane's Laboratory Prototype Dual-Loop Triple-Effect Chiller

Once the Trane/GRI dual-loop, triple-effect program was underway, DOE and ORNL identified and evaluated other promising alternative multiple-effect technologies. A double-condenser coupled (DCC) concept emerged as the best alternative [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. The York laboratory prototype triple-effect chiller was operated at different loads for approximately 2,400 hours through December 2000 (see Figure 4), with no unusual accumulation of non-condensibles in continuous operation. The COP was close to theoretical predictions of 30% higher efficiency compared to comparable double-effect absorption chillers. This York full-size prototype was indirectly fired using a heat transfer fluid for the high stage generator, making this technology a natural fit for higher-temperature waste recovery in large Integrated Energy Systems.



Fig. 4. Triple effect, indirect-fired absorption chiller tested at York International, York, Pennsylvania.

The final phase of work, construction of a direct-fired field test triple-effect chiller prototype, factory testing, and a field test demonstration in Clark County, Nevada, has been completed. 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 field-tested during the summer of 2002 (see Figure 5).



Fig. 5. 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).

6 EDUCATION

As has been previously reported, DOE supports training and education activities. Two books have been published under DOE co-sponsorship. The first book, *Absorption Chillers and Heat Pumps*, [16] was written for undergraduate students to introduce them to fluid mixtures, absorption cycles, and absorption equipment. The second book, *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 2001, the United States Department of Energy (DOE) has made a significant shift in focus for development and use of Thermally Activated Heat Pumping Technologies. DOE is working with partners from the heating and cooling industry and the power generation industry to develop Integrate Energy Systems (IES) using advanced thermally driven heat pump technologies for building heating and cooling by recycling otherwise wasted heat from electric generating equipment. The first products resulting from this industry government partnership for development of new Integrated Energy Systems entered the market in 2004.

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 can add significant additional cooling when combined with higher temperature waste heat power generating equipment compared to single-effect and double-effect chillers.

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 or exceeding 80%.

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