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**DISTRICT HEATING AND COOLING
TECHNOLOGY DEVELOPMENT PROGRAM:**

**Phase II -- Investigation of Reduced-Cost Heat-Actuated
Desiccant Cooling Systems for DHC Applications**

Final Report

Report Period: August 20, 1990 to January 1, 1992

By

K.D. Patch, F.A. DiBella, and F.E. Becker

February 1992

**Work Performed Under Contract No. DE-FG01-90CE266032
August 20, 1990 to January 1, 1992**

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ABSTRACT

A detailed assessment has been completed of the use of desiccant-based customer-sited heat-actuated cooling for District Heating and Cooling (DHC) systems, showing that introduction of a reduced-cost desiccant cooling system would result in widespread market penetration. Due to the heat-actuated nature of desiccant cooling systems, conventional two-pipe district heating (DH) systems could be operated as DHC systems without the major capital expense of adding two new chilled water distribution pipes. Further, desiccant-based DHC systems can be operated with low-grade DH-supplied heat without significant loss in operating capacity, relative to absorption chillers.

This program consisted of three principal components: a market study of existing and future reduced-cost liquid desiccant cooling (LDC) systems; an examination of the installed costs of these existing and reduced-cost LDC systems; and four detailed case studies. Both the installed cost and equivalent chilled water cost of existing large LDC systems were found to be quite competitive with district chilled water, while the high capital cost of small LDC systems made them more expensive than district chilled water. Potential total system sales in this existing large-scale LDC market are quite low, since most of the market for DHC space conditioning is in smaller equipment sizes. Cost savings realized from producing a reduced-cost LDC system would result in small LDC systems (sized well below 6,000 cfm) becoming competitive with the current range of district chilled water costs. The increased economic attractiveness of reduced-cost LDC systems would lead to a sales volume increase that was estimated to equal about 5,000 units annually. It was recommended that LDC technology be made more accessible to the DHC community, through either a hardware demonstration, marketing assistance and technology transfer, or by convincing a manufacturer to produce the reduced-cost LDC systems.

In conclusion, a trend towards increasing worldwide-levels of DHC is emerging. Heat-actuated cooling will certainly play a major role in this development. By making LDC technology more accessible to the DHC community, desiccant cooling will be able to take its place among the range of attractive heat-actuated cooling options.

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1. INTRODUCTION AND SUMMARY

This is the final report for DOE Project Number DE-FG01-90CE266032 entitled "District Heating and Cooling Technology Development Program: Phase II – Investigation of Reduced-Cost Heat-Actuated Desiccant Cooling Systems for DHC Applications." The principal objective of this program is to examine the application of low-cost heat-actuated liquid desiccant cooling systems in two-pipe District Heating (DH) systems.

This final report covers project work conducted from August 20, 1990 to January 1, 1992. The goals of the project are based on the desire to lower the operating temperature of the transport medium in a DH system while still enabling district cooling (DC) via that transport medium. At this time a district heating and cooling (DHC) system must use a four-pipe heating and cooling delivery system – two pipes for hot water supply and return and two pipes for chilled water supply and return if both heating and cooling are to be provided. Unfortunately, such a four-pipe system is expensive, especially for existing DH systems that already have a two-pipe system installed.

The suggested solution is to use a two-pipe DH delivery system with a customer-installed heat-actuated cooling system. In this manner, the heat supplied by the district heating system can be used throughout the year. The concept is thought to represent a viable approach for reducing the high first costs of DHC systems by eliminating centrally located, dedicated chillers and the need for dedicated chilled water distribution network piping.

Currently there are two types of heat-actuated cooling systems: absorption and desiccant-based. Both types of systems were first commercialized decades ago and represent well-developed technologies. Through the years, however, absorption chiller systems have become better known and established in the comfort cooling market.

Absorption chillers can be heated with 200°F to 250°F hot water; however, below 200°F these chillers operate at markedly reduced efficiencies. Absorbers must make up for this low-temperature performance deficiency by markedly increasing their size for a given specific cooling demand. In fact, employing thermally-actuated absorption chillers in DH systems that use transport fluid temperatures below 180°F is generally not recommended. In this regard, desiccant-based heat-actuated cooling systems have a distinct advantage over absorption chiller-based systems. Desiccant systems have the ability to efficiently utilize lower regeneration (heat input) temperatures, where the use of absorption chillers is not recommended. Accordingly, desiccant-based heat-actuated systems should be

viewed as a viable alternative engineering choice for new hot water-based DHC systems, as well as for DH sites that are upgrading older absorption chiller systems.

Tecogen Inc. sees a significant future role in heating, ventilating, and air-conditioning (HVAC) applications for desiccant-based cooling systems. Desiccant-based HVAC systems are attractive and well worth additional engineering evaluation in district heating and cooling applications because: they are efficient, they can provide independent humidity and temperature control to conditioned spaces, they do not use CFC (chlorinated fluorocarbon) working fluids, and they have biocidal and virucidal (air purification) characteristics.

The current Phase II investigation was begun as a result of the previous Phase I program's positive results. The Phase I work found that while operating costs of liquid desiccant cooling (LDC) equipment were quite attractive, reducing the cost of existing LDC equipment designs was essential if significant market penetration was to occur. Consequently, the Phase II work delved into a cost reduction study of heat-actuated liquid desiccant space cooling equipment, which involved modifying equipment from the closely related field of cooling towers. The main design criteria of cooling towers are similar to those of liquid desiccant systems; that is, spreading a liquid over a large surface area in order to allow good liquid/air contact while minimizing parasitic energy usage. The Phase II work also included a study of the LDC equipment market and culminated in four geographically-distinct economic case studies.

The following final report summarizes the work conducted during the project. The major findings include:

- Existing large LDC system installed costs were below the average level of recent DC-supplied chilled water system costs;
- The equivalent chilled water cost of existing large LDC systems is slightly below that of low-cost 15 cent/ton-hour district chilled water;
- Total system sales in this large-scale LDC market are quite low, since most of the DHC space conditioning market exists in smaller equipment sizes;
- Cost savings realized from producing a reduced-cost LDC system would result in LDC system installed costs becoming competitive with DC chilled water systems down to a size range of 10,000 cfm;

- The equivalent chilled water cost of reduced-cost moderate- and large-sized LDC systems would be 3 cents/ton-hr below low-cost 15 cent/ton-hr district chilled water;
- A reduced-cost design would result in small LDC systems (sized well below 6,000 cfm) becoming competitive with the current range of district chilled water costs;
- The increased economic attractiveness of reduced-cost LDC systems would lead to a sales volume increase that was estimated to equal about 5,000 units annually;
- It was recommended that LDC technology be made more accessible to the DHC community, through either a hardware demonstration, marketing assistance and technology transfer, or by convincing a manufacturer to produce the reduced-cost LDC systems; and
- A need was identified for a modified form of simple dry-bulb-based cooling degree days, which would allow for estimation of relative humidity (latent cooling) effects on energy consumption.

In conclusion, a trend towards increasing worldwide levels of DHC is emerging. Heat-actuated cooling will certainly play a major role in this development. By making LDC technology more accessible to the DHC community, desiccant cooling will be able to take its place among the range of heat-actuated cooling options.

2. TECHNICAL DISCUSSION

2.1 LOW-GRADE HEAT-ACTUATED COOLING OPTIONS

Of the presently available technology options for heat-actuated cooling, only a few have been demonstrated to be commercially viable in space cooling applications. These can be broadly categorized as absorption cooling and desiccant cooling.

2.1.1 Absorption Cooling

Closed-cycle absorption machines commonly utilize a liquid absorbent as a secondary fluid to absorb the primary fluid – gaseous refrigerant – which has been vaporized in the evaporator. The closed-cycle absorption cycle and the vapor compression cycle have in common the evaporation and condensation of a refrigerant liquid (these processes occurring at two pressure levels within the unit). The two cycles differ in that the absorption cycle uses a small liquid pump to produce the pressure differential, while the vapor compression cycle uses a vapor compressor that has a relatively large usage of primary energy. A schematic of a typical absorption cycle water chiller is shown in Figure 2.1.

While closed-cycle absorption technology is well-developed and offers many unique features, at heat source temperatures below 200°F the performance of these systems degrades very rapidly. This is illustrated in Figure 2.2, which shows the effect of regeneration temperatures on the cooling capacity of an absorption cycle which has been optimized for low temperatures. Figure 2.2 also highlights the superior performance of a typical open-cycle desiccant-based cooling system. Desiccant-based cooling systems are discussed in more detail below.

2.1.2 Desiccant Cooling

Open-cycle desiccant-based cooling systems utilize a desiccating (or drying) material to remove moisture from air being conditioned. The dehumidification process is essentially adiabatic, converting the latent energy of the water vapor to sensible energy of the air, resulting in an increase in the air temperature. However, dehumidification combined with heat rejection results in an overall cooling of the air. This process is shown on a psychrometric chart in Figure 2.3. The desiccant material can be regenerated by applying low-grade heat to drive off the absorbed moisture.

Figure 2.4 illustrates the conceptual design of an open-cycle liquid desiccant cooling (LDC) system. There are two major subassemblies in an LDC system;

Figure 2.1 Typical Absorption Cooling Cycle

Figure 2.2 Effect of Regeneration Temperature on Cooling Capacity

Figure 2.3 Desiccant Cooling Processes

Figure 2.4 Typical Liquid Desiccant Cooling System Configuration

the desiccant dehumidifier or conditioner assembly, which removes moisture and produces conditioned air, and the desiccant regenerator assembly, which releases that moisture to exhaust air. The conditioner assembly is composed of the conditioner component, which is a heat and mass transfer device similar to a cooling tower; a heat exchanger (not shown), which removes heat from the system; a conditioned air blower (not shown); and a desiccant transfer pump. The regenerator assembly is composed of the regenerator component, which is a heat and mass transfer device similar to a cooling tower; a heat exchanger (not shown), which adds heat to the system; an exhaust air blower (not shown); and a desiccant transfer pump.

Moisture removed in the conditioner is absorbed in the recirculating cooled desiccant solution, causing the solution to become more dilute. A slip stream of the dilute solution is removed to the regenerator. In the regenerator, the absorbed moisture is stripped from the heated dilute solution, humidifying the exhaust air, and thereby producing concentrated desiccant solution. A slip stream of concentrated desiccant is directed to the conditioner in order to replenish the dilute solution, completing the cycle.

There are two basic ways that desiccant dehumidifiers can be utilized in heat-actuated cooling systems. In both of these depictions, the desiccant dehumidifier system consists of an open-cycle absorption system coupled to a heat source. The desiccant dehumidifier is used to convert the latent energy in the process air to sensible energy. Alternative means are then used to remove the sensible energy in the process air, producing cool dry air for the building.

In the first method, as shown in Figure 2.5, heat-actuated dehumidification provides a sensible-only load for an electric vapor-compression or heat-actuated absorption system. This sensible load can be reduced by heat rejection from the warm over-dry air. Sensible-only loads can be more efficiently met by a vapor-compression or absorption system, resulting in various operational advantages. Such a combination can be described as an integrated latent/sensible cooling system.

The second method of performing sensible cooling is based on the concept of direct evaporative cooling of an over-dry air stream. Figure 2.6 shows this cycle as comprising two separate, basic, and proven air processors. The desiccant cooling system is similar to that of Figure 2.5, but is operated to produce air that is much drier than required for supply to the conditioned space. The direct evaporative cooler is used to adiabatically cool the over-dry process air to the desired supply conditions. This evaporative cooling process is similar to that used

Figure 2.5 Integrated Latent/Sensible Cooling System

Figure 2.6 Desiccant-Based Total Cooling System

for space conditioning in hot and dry regions of the world, where over-dry outdoor air is humidified for cooling buildings.

Either method of using desiccant cooling will provide excellent control over building space conditions. Cooling system operation can be varied to provide either high dehumidification, or to provide a high degree of sensible cooling. This feature provides exceptional control over both temperature as well as humidity. Applications are often found for desiccant cooling when such independent control of temperature and humidity is critical.

2.2 DESICCANT BACKGROUND

Although much of the hardware and many of the components used in sorption systems are familiar to the heating, ventilating, and air-conditioning (HVAC) engineer, the sorption process is quite complex and does not lend itself to the intuitive approach to design. The control of these systems is unlike the simple on-off control of vapor compression air conditioners, and the thermodynamic cycle utilized may vary to maximize performance in different climates.

2.2.1 Desiccant Materials

There are two classes of desiccant materials: those which adsorb, which are solid materials, and those which absorb, generally liquids. Both processes selectively remove a substance, water in this case, from a process stream (air) during the adsorption or absorption process and release the substance to another stream during desorption or regeneration. Absorption differs from adsorption in that during the former process, the chemical composition of the absorbent changes whereas in adsorption it does not.

The most commonly used liquid desiccant is a lithium chloride (LiCl) salt and water solution. When a concentrated LiCl solution is sprayed into moist air the water vapor in the air is absorbed to form a weaker, more dilute LiCl solution. The weak solution is regenerated by adding heat to drive off the absorbed moisture and concentrate the solution. Air is generally used to carry the moisture away. Triethylene glycol is another popular liquid desiccant.

The adsorbing solid desiccants, which include silica gel, molecular sieves, and activated alumina, adsorb water molecules into "pores" in their molecular structures. The water does not react with the desiccant but is held in the crystalline matrix by attractive molecular forces. These solid desiccants contain large internal surface area-to-weight ratios. A typical grade of silica gel contains 800 m² per gram.

The ultimate adsorbing capacity of a desiccant is a function of water vapor pressure in the air adjacent to the material, or for any given equilibrium temperature is a function of relative humidity. This dependence is illustrated in Figure 2.7 for various solid desiccants. Silica gel has a very high capacity, reaching 40 lb of water per 100 lb of silica gel. This is one important property of a desiccant since the higher the capacity, the less material is needed so that volume and cost can be minimized.

2.2.2 Desiccant Dehumidifiers

Desiccant dehumidifiers used in desiccant-based cooling systems are of two types: liquid and solid.

Liquid desiccant dehumidifiers are most commonly of the type shown in Figure 2.8. There are two principal components: a conditioner, in which concentrated desiccant solution is used to dry the air being processed for use in the conditioned space, and a regenerator, in which the desiccant solution is heated and placed in contact with air to drive off the absorbed moisture.

There are various designs for both components. The conditioner requires cooling to remove the liberated heat of absorption. This waste heat removal may be accomplished with air, chilled water, or cooling water from a cooling tower.

Available systems, largely from Somerset Technologies and marketed under the name Kathabar, are rugged, expensive, and designed mainly for industrial drying. A number of approaches are being examined for reducing the cost of such units to make them more applicable to conventional space-conditioning.

Solid desiccant dehumidifiers are typically as shown in Figure 2.9. A rotating desiccant wheel passes the desiccant alternately through a hot air stream, which dries the desiccant, and a process air stream, which is being dried.

These units are also typically designed for an industrial environment. Manufacturers like Bry-Air and Airflow sell systems using silica gel granules. Cargocaire sells a system designed this way but using LiCl held onto a neutral substrate.

2.2.3 Commercial Desiccant Dehumidification Systems

Commercial-size and industrial-size desiccant dehumidification systems are found in many applications for control of humidity in conditioned space for hospitals, manufacturing plants, warehouses, hotels, etc. They are also used in a

Figure 2.7 Comparison of Relative Humidity Effect on Various Desiccants

Figure 2.8 District Heating-Based Liquid Desiccant Cooling System

Figure 2.9 Typical Solid Desiccant Dehumidifier

variety of manufacturing and processing operations in the food, chemical, steel, plastic, and electronics industries. Systems have been built to handle air flows from 1000 to over 100,000 scfm. Hot water temperatures as low as 100°F have been used for regeneration.

Kathabar Systems, Somerset Technologies Inc., is a major manufacturer of desiccant dehumidification systems. Kathabar, founded in 1933, has a significant amount of technical expertise in this technology and has been assisting us in the selection of appropriate hardware. Tecogen Inc. has been working with Kathabar for several years on a number of development programs directed toward applying desiccant dehumidification to the field of comfort cooling. The important point to be emphasized is that desiccant technology is not new and has been applied in many areas. What distinguishes this proposed concept is that such benefits can be gained when the technology is applied to space cooling for DHC systems.

3. BENEFITS OF DESICCANT COOLING SYSTEMS

There are several benefits that can be realized by using desiccant cooling systems in general, and in conjunction with district heating systems in particular. These advantages serve to increase occupant comfort levels and decrease operating costs.

- As shown in Figure 2.2, desiccant-based systems can be operated using low grade DH-supplied heat without significant loss in operating capacity.
- In certain configurations, e.g., liquid desiccant-based systems, the concentrated desiccant can be produced in off-peak hours and stored, effectively storing the cooling. This can be used to smooth out the cooling load requirements. Liquid systems also offer the option of distributed humidity/temperature control with central regeneration.
- Sensible and latent capacity can be controlled independently, resulting in various benefits. Occupants have improved control over the space conditions and can set the temperature and humidity independently. It is well recognized that maintaining lower space humidities allows higher temperature set points to be used without any reduction in comfort.
- In integrated desiccant dehumidification/sensible cooling systems, the efficiency of the sensible cooling process can be increased by raising the evaporator temperature. Raising the evaporator temperature above the dew point of the conditioned air is possible because dehumidification is effected prior to sensible cooling, allowing more efficient operation of the sensible cooling process.
- Since they retain operating effectiveness even when processing 100-percent ventilation air, desiccant systems have the potential to dramatically improve indoor air quality.
- The district heating system can be utilized year-round, increasing the return on investment.
- Desiccant cooling systems do not require any chlorinated fluorocarbons for their operation.
- Since the district heating system only has to supply hot water (or steam) to the users, systems that were designed as conventional two-pipe DH systems can now be operated as district heating and cooling systems without major additional capital expense.

The LDC system enables year-round ventilation without any loss of efficiency or capacity and at a negligible cost premium. Also, by clearing indoor air of pollutants, the LDC system dramatically improves air quality. This can be especially important in the tight construction typical of modern energy-efficient buildings.

Sensible and latent capacity can be controlled independently, resulting in various benefits. Occupants have improved control over the space conditions and can set the temperature and humidity independently. High dehumidification without overcooling and wasteful reheating can be achieved easily by the LDC system. This is critically important in applications where the interior latent loads are high. Similarly, high sensible heat ratios are possible. Independent control of the sensible and latent capacities in this manner can be achieved without loss of efficiency or total capacity.

Under certain dry conditions, the space can be conditioned without any thermal input. This is accomplished by operating the system in a regenerative evaporative cooling or heat recovery/heat exchange mode. When cooling is needed, the system operates as an indirect evaporative cooler or a direct evaporative cooler, or both. When only ventilation is needed, the system operates in the heat recovery/heat exchange mode. The system design and components readily allow these operating modes, but at higher efficiencies than those of conventional evaporative systems.

4. CASE STUDY INVESTIGATIONS OF HEAT-ACTUATED DESICCANT COOLING

This task continued the case study investigations that were initiated in the first phase of this project (Department of Energy Contract Number DE-FG01-89CE26593). As a result of the Phase I work, four unique institutions were selected for additional study in Phase II. The current project phase performed an energy and cost analysis for these sites. The analysis compared the economics of current-cost and reduced-cost heat-actuated liquid-desiccant installations at the four sites.

4.1 SITE DESCRIPTIONS

4.1.1 District Energy (St. Paul, Minnesota)

The St. Paul City Hall/Ramsey County Courthouse Building is the first of the four case study sites for the current liquid desiccant cooling (LDC) system study. The St. Paul City Hall was first identified and studied in the previous Phase I portion of this work. The City Hall is a customer of District Energy St. Paul, and is located in St. Paul, Minnesota. The LDC equipment for this site would be sized at 6000 scfm of outside makeup air.

This site was chosen to represent one of the two main types of district heating (DH) system customers: those using district hot water. District Energy St. Paul is representative of the modern variable-temperature hot-water DH systems, with a system water supply temperature that ranges from a maximum of 250°F when the outside air temperature design point of -20°F is reached, to a minimum of 190°F when the outside air temperature is above 40°F. Additionally, as a governmental building, it represents one of the most common DH customer types. Summer ambient air design conditions are 92°F and 104 gr/lb of moisture. There are 8,282 (base 65°F) annual daily heating degree days and 894 (base 65°F) annual daily cooling degree days in Minneapolis, Minnesota. Cost of DH-supplied hot water in St. Paul is \$9.74/MMBtu.

4.1.2 Toronto District Heating Corporation (Ontario, Canada)

The Toronto Hospital, Toronto General Division (TGH) is the second of the four case study sites. Similar to the St. Paul City Hall, the TGH site was first identified and studied in the previous, Phase I portion of this work. TGH is a customer of the Toronto District Heating Corporation (TDHC) and is located in downtown Toronto, Ontario, Canada. TDHC operates a steam DH system, operating at a 200-psig saturated steam distribution pressure. Desiccant equipment was chosen to be installed on an existing air handling zone that used 75,000 scfm of 100 percent fresh air with no recirculation.

TGH was chosen to represent the second main type of DH system user, as it is connected to a steam DH system. Additionally, being a hospital, TGH represents another likely DH system user. Summer ambient air design conditions are 90°F and 95 gr/lb of moisture. There are 3,646 annual daily heating degree days, and 625 (base 65°F) annual daily cooling degree days in Toronto. Average steam costs in Toronto are \$6.12/MMBtu.

Information was collected and analyzed regarding the heating, ventilating, and air-conditioning equipment used at the TGH site. This information was collected in order to detail the potential market of low-cost liquid desiccant cooling system sizes for this study. Figure 4.1 illustrates the sizing information that was gathered during this effort. This figure diagrams the cumulative number of supply air systems at TGH, where each point represents the individual control zones in which an LDC system could potentially be installed. Half of the zones are below a system size of about 10,000 cfm, and half are larger than 10,000 cfm. The average control zone size is 15,000 cfm. In other words, these data reveal that a moderate-sized LDC system unit installation at TGH would have a flow capacity of 10,000 to 15,000 cfm. This TGH data suggest that for the district cooling (DC) market, a small LDC installation would involve less than 15,000 cfm of conditioned air, while a large LDC system would condition airflows that are larger than 15,000 cfm.

4.1.3 Boston Thermal Energy Corporation (Massachusetts)

The third case study site selected was the Museum of Fine Arts (MFA), Boston. Several reasons contributed to the selection of the MFA as one of the cases:

- Museums represent desirable DH customers that are often found in the core downtown areas served by many DH systems;
- The MFA used to be serviced by the Boston Thermal Energy Corporation steam DH network, and thus represents DH customers who have abandoned DH service but may be able to be reconvinced of the advantages of DHC;
- As a forward-looking fine arts museum, the MFA is currently in the midst of a multi-year program involving an upgrade of their climate control system, including the addition of dehumidification/humidity control;

Figure 4.1 Cumulative Number of Supply Air Systems at Toronto General Hospital

- The MFA is in need of additional cooling/dehumidification control capacity, and would be well served by the addition of an LDC system; and
- The MFA is located in Boston and is convenient to Tecogen's offices.

Boston summer ambient air design conditions are 91°F and 93 gr/lb of moisture. There are 5,690 (base 65°F) annual daily heating degree days and 674 (base 65°F) annual daily cooling degree days in Boston. Steam supplied by Boston Thermal costs \$10/MMBtu on a combined heating/cooling rate and \$7/MMBtu for a cooling rate. It was assumed that a moderate-sized 20,000-scfm unit of LDC equipment would be added at the MFA.

4.1.4 St. Louis Thermal Energy (Missouri)

The fourth case study was located in the service area of St. Louis Thermal Energy due to the significant summertime cooling load of a Missouri-based location. St. Louis Thermal Energy (SLTE) operates a 150-psig steam DH system that does not yet have any heat-actuated cooling customers. St. Louis summer ambient air design conditions are 98°F and 94 gr/lb of moisture. There are 4,904 (base 65°F) annual daily heating degree days and 1,475 (base 65°F) annual daily cooling degree days in Kansas City, Missouri. A long-term contract for DH-supplied steam would result in a cost of \$13.90/MMBtu; an \$7/MMBtu interruptible steam rate that is suitable for summertime cooling is also available.

SLTE has identified a potential site for analysis as a case study – a large shopping mall that is not yet a customer of SLTE. This mall is typical of the sites that own their own boilers and air-conditioning equipment and would become customers of the local DH system if their energy costs warranted the change.

The shopping mall would be an ideal case study for this program since it is currently in need of additional air conditioning capacity to solve a humidity problem. During the summer the mall's cooling system is often unable to meet the required humidity removal requirements, and on occasional hot days it is unable to maintain the desired temperature setting. The shopping mall has about 1000 tons of air conditioning installed and requires about 200 tons of supplemental air conditioning. A cost-competitive heat-actuated LDC system of perhaps 80,000-cfm capacity would solve this mall's cooling problem.

4.2 OPERATING COST ANALYSIS

Table 4.1 summarizes the pertinent design information for the four case study locations. The main conclusion apparent in the data is that for the four sites examined, there is no major difference in the design cooling load conditions. Only eight degrees separate the maximum dry bulb temperature from the minimum, and there is a moisture level difference of only 1.1 grains per pound between the extremes. In other words, one design style of LDC equipment should satisfy a specific building cooling application in any of the four temperate locations studied. Dehumidifying ambient air in St. Paul on the hottest summertime design day is not much different from dehumidifying ambient air in St. Louis.

One of the goals of this program was to investigate the utility of low-temperature district heat for summertime cooling applications. Consequently, even though high-pressure district steam could have been used to provide lower energy and capital costs at three sites, LDC system performance was estimated using 200°F district hot water. Accordingly, 2000 Btu/lb of moisture removal was used for energy use calculations in all four locations.

The resultant hourly variable operating cost of liquid desiccant cooling equipment in these locations is shown in Figure 4.2. Costs vary between a maximum of \$57.34/hr for the 80,000-scfm LDC unit located at St. Louis, to \$3.02/hr for the 6,000-scfm unit at St. Paul.

Now that the hourly energy cost of LDC equipment was available, it was necessary to calculate the annual utilization of the cooling equipment in the four locations. Utilization of cooling equipment in various locations can be grossly modeled on the basis of simple cooling degree days. Simple dry-bulb-based cooling degree days are not based on the actual physical process of space cooling (they neglect the dehumidification, or latent load that is involved), but represent the only simple measure of summertime cooling energy usage that is widely accepted and tabulated.

The number of simple cooling degree days (CDDs) on a given day is calculated by taking the average of the daily maximum and daily minimum dry bulb temperatures and subtracting that value from a base temperature of 65°F. For example, if on a particular day the daily temperature ranged between 60°F and 90°F, that day would possess ten cooling degree days (75°F average daily temperature less 65°F base temperature). The daily numbers of cooling degree days are then summed on a seasonal basis, yielding a number that is proportional to the sensible cooling load for that time period. Table 4.1 summarizes the average annual cooling degree days for each of the four study sites.

TABLE 4.1
CASE STUDY SUMMARY DATA

Location	Summer Ambient Design Dry Bulb (F)	Summer Ambient Design Moisture Level (gr/lb)	Average Daily Cooling Degree Days (65°F Base)	Cost of DH-Supplied Energy (\$/MMBtu)
St. Paul, Minnesota	92	104	894	9.74
Toronto, Ontario	90	95	625	6.12
Boston, Massachusetts	91	93	674	7.00 to 10.00
St. Louis, Missouri	98	94	1475	7.68 to 13.90

Figure 4.2 Variable Operating Cost of Liquid Desiccant Cooling Equipment

Locations with larger numbers of annual cooling degree days represent locales with longer and/or hotter summers. For example, if a particular building was moved from Toronto to St. Louis, over twice as much cooling energy would be used in the new location (1475 CDDs divided by 625 CDDs result in 2.4 times as much cooling energy). Consequently, although it would be possible to install similarly designed cooling equipment in the four case study locations, St. Louis-based equipment would have the highest seasonal energy consumption and would represent the best location to install LDC equipment. Although St. Paul has a slightly higher design moisture level, St. Louis has a much higher number of cooling degree days, thus St. Louis has a greater need for summertime cooling.

Accordingly, 2000 hours annually of equivalent full-load operation in Toronto was assumed for the design basis of this analysis. The CDD method was then used to make a first-order correction to the other locations. Figure 4.3 shows the total annual variable operating cost of the selected LDC equipment at the four study sites. Energy costs vary between \$270,830/yr for the 80,000-scfm LDC unit located at St. Louis, to \$8,636/yr for the 6,000-scfm unit at St. Paul.

Finally, the economic viability of the proposed LDC equipment can be decided once its fixed cost is determined. The next section compares the economics of both existing and reduced-cost designs of LDC equipment to alternative cooling supply methods.

4.3 TOTAL COST ANALYSIS

District cooling-supplied chilled water represents the alternative cooling supply method available to district energy system operators and building owners and operators. These principals would consider using LDC equipment if its total cost was less than conventional 15 to 30 cents/ton-hour chilled water delivery, or if there were other overriding tangible benefits. Other sections of this report discuss the tangible advantages of using LDC equipment; i.e., it is efficient, it can provide independent humidity and temperature control to conditioned spaces, it does not use CFC (chlorinated fluorocarbon) working fluids, and it has biocidal and virucidal (air purification) characteristics. This report section discusses the attractive total cost of operating LDC equipment and shows that tangible benefits (including the fact that LDC systems do not use CFCs) only serve to make LDC systems more attractive.

Figure 4.3 Annual Variable Operating Cost of Liquid Desiccant Cooling Equipment

4.3.1 Economic Viability of Existing LDC Equipment

The total fixed cost of the four case study installations was approximated to equal the installed system costs outlined in Table 5.1 and Figure 5.1 (which appear in Section 5 of this report). Installed system costs for the existing LDC equipment ranged between \$90,000 for the 6,000-scfm St. Paul installation, to \$313,000 for the 80,000-scfm unit at St. Louis. The installed cost per cfm of the two large LDC systems being studied was equal to low-cost DC systems. To avoid distorting effects due to taxes, it was assumed that a nonprofit tax-exempt district energy supplier would own and operate the cooling equipment. In order to calculate the annual fixed cost of the LDC equipment, it was assumed that a 12 percent simple-interest ten-year loan would be sufficient to amortize the installation. Resultant annual capital charges range between \$14,243 in St. Paul to \$49,668 in St. Louis. Finally, the annual costs were converted to a cost per ton-hour basis in order to be readily compared to current district chilled water costs.

Figure 4.4 contains the results of adding these fixed cost calculations to the four sites' variable costs. Examination of the pricing trends shows that for Toronto and St. Louis, the two largest installations, LDC equipment represents the low-cost cooling option. The total cooling cost at these two sites is slightly below that of low-cost district chilled water. Use of LDC equipment in Boston is no more costly than average-priced chilled water. Only at St. Paul, the smallest LDC system installation, is DC-supplied chilled water less expensive than desiccant cooling.

Thus, the total energy cost results displayed in Figure 4.4 follow the same trends as the installed cost results shown in Figure 5.1. The larger LDC installations represent below-average installed costs, and due to their favorable operating costs these installations represent the lowest total cost district cooling alternative. Moderate-sized LDC installations are above average in installed cost, but moderate operating costs result in an average annual total cost. Small-sized LDC installations are well above the range of DC system installed costs, but when combined with modest operating costs become only slightly above the range of current acceptable chilled water costs.

Obviously, using reduced-cost LDC equipment will provide additional reductions to the equivalent chilled water cost of these LDC installations. The next section examines the magnitude of these savings.

Figure 4.4 Equivalent Chilled Water Cost of Existing Liquid Desiccant Cooling Equipment

4.3.2 Improved Economics of Reduced-Cost LDC Equipment

The market study conducted in this project revealed that existing LDC equipment sales represent only a tiny fraction of overall U.S. cooling systems sales. The market study examined how a redesigned low-cost LDC system would affect annual sales volume. A conservative estimate was made that a potential 3304 percent increase in annual LDC system sales was possible due to the improved volume resulting from the lowered cost. In the largest equipment size, the installed cost of low-cost LDC equipment was predicted to become 9 percent below the range of current DC system installed costs. Consequently, large high-volume LDC equipment was found to represent the lowest installed-cost district energy option.

The total fixed cost of the four reduced-cost case study installations was calculated from the installed system costs outlined in Table 5.3 and Figure 5.2 (which appear in Section 5 of this report). Installed system costs now ranged between \$59,000 for the 6,000-scfm St. Paul installation, to \$240,000 for the 80,000-scfm unit at St. Louis. Again, it was assumed that a nonprofit tax-exempt district energy supplier would own and operate the cooling equipment. In order to calculate the annual capital cost of the LDC equipment, it was again assumed that a 12-percent simple-interest ten-year loan would be sufficient to amortize the installation. Resultant annual capital charges range between \$9,398 in St. Paul, to \$38,053 in St. Louis. Finally, the annual costs were converted to a cost per ton-hour basis in order to be readily compared to current district chilled water costs.

Figure 4.5 contains the results of adding these fixed cost calculations to the four sites' variable costs. Examination of the pricing trends shows that for Boston, Toronto, and St. Louis, the three largest installations, LDC equipment represents the lowest total-cost cooling option. Use of LDC equipment in any of these locations would be three cents per ton-hour less expensive than DC-supplied chilled water. At St. Paul, the smallest LDC system installation, the total cost of operating low-cost LDC equipment is comparable to average-cost DC chilled water.

Thus, the total energy cost results displayed in Figure 4.5 show an improvement relative to the total energy costs of existing LDC equipment shown in Figure 4.4. Economies due to increased production volume have lowered the installed costs of LDC equipment, resulting in significantly reduced system operating costs. The installed costs of moderate- and larger-sized LDC installations are below the average of existing DC system installed costs; due to their favorable operating costs these LDC installations represent the lowest total cost district cooling alternative. Small-sized high-volume LDC installations continue to be well above the average DC system installed cost, but their moderate operating costs result in an equivalent chilled water cost that matches that of mid-priced DC system.

Figure 4.5 Equivalent Chilled Water Cost of Low-Cost Liquid Desiccant Cooling Equipment

4.4 CONCLUSIONS

Design data for four geographically distinct sites were compiled so that individual case studies could be done. These sites were located in the service area of District Energy St. Paul (Minnesota), Toronto District Heating Corporation (Ontario, Canada), Boston Thermal Energy Corporation (Massachusetts), and St. Louis Thermal Energy (Missouri). LDC cooling systems under consideration ranged from a 6000-scfm unit at St. Paul to an 80,000-scfm installation at St. Louis.

Only moderate differences in the instantaneous design cooling load were observed at the four sites. Consequently, one design style of LDC equipment should satisfy a specific cooling application in any of the four temperate locations. However, major differences were established between the seasonal cumulative cooling energy usage of the four sites – for a particular application, 2.4 times the seasonal cooling energy usage was found to be required in St. Louis, compared to Toronto. A need was identified for a modified form of simple dry-bulb-based cooling degree days, which would allow for accurate estimation of humidity (latent cooling) effects on energy consumption.

An economic analysis was completed for each site, comparing conventional centrally-supplied district chilled water to customer-sited district heat-actuated LDC equipment. District chilled water costs were taken to range between 15 and 30 cents/ton-hr. The LDC analyses involved computations of variable (energy) costs, as well as fixed (capital) costs for two types of equipment:

- Existing LDC equipment, and
- Reduced-cost LDC equipment.

Hourly operating costs for the LDC equipment varied between \$3.02/hr at St. Paul to a maximum of \$57.34/hr at St. Louis. Corresponding annual operating costs ranged between \$8,636/yr and \$270,830. Installed system costs for the existing LDC equipment ranged between \$90,000 for the 6,000-scfm St. Paul installation to \$313,000 for the 80,000-scfm unit at St. Louis. Installed system costs for the reduced-cost LDC equipment ranged between \$59,000 for the 6,000-scfm St. Paul installation to \$240,000 for the 80,000-scfm unit at St. Louis.

These variable and fixed costs were expressed on a cost-per-ton-hour basis and compared to current district chilled water costs. The cooling cost of both existing and reduced-cost LDC systems in Toronto and St. Paul were found to be below average district chilled water costs; reduced-cost LDC systems at these two sites clearly represented the lowest-cost district cooling option. The equivalent

chilled water cost of an existing moderate-sized LDC system in Boston equalled current average-priced district chilled water; a reduced-cost LDC system in Boston provided low-cost district cooling that was comparable to that found in Toronto or St. Louis. The equivalent chilled water cost of the existing small 6000-scfm LDC installation in St. Paul was above the range of current alternative DC costs; using a reduced-cost LDC system resulted in an equivalent chilled water cost that was comparable to the average current DC cost.

In conclusion, the total cooling cost of large, currently produced LDC systems is slightly below low-cost 15 cents/ton-hour district chilled water. Future low-cost moderate- and large-sized LDC systems would produce cooling at a cost that is 3 cents/ton-hr lower than current low-cost district chilled water. Thus, existing large liquid desiccant cooling systems are economical in today's DHC environment; a reduced-cost LDC design would extend the economic range of this technology to much smaller sizes.

5. DESICCANT EQUIPMENT COST REDUCTION STUDY

In determining whether or not the installed cost of existing customer-sited liquid desiccant cooling (LDC) systems was competitive with alternative district cooling (DC) methods, it was found that avoiding the expense of in-ground district chilled water distribution piping by using district heating (DH) piping for cooling purposes resulted in the installed cost of existing large LDC systems equalling the cost of existing DC systems. These results are discussed in this chapter, as is the broader cost-competitive range of cost-reduced LDC equipment.

5.1 EXISTING LDC SYSTEM INSTALLED COSTS

Nonseasonal district chilled water is the alternative conventional cooling method chosen to be compared with LDC. A survey of such recent and proposed district cooling installations was conducted in order to collect DC system installed cost data. Survey results were used to establish a range of current cooling system installed costs. Installed costs ranged between \$21,000,000 for a 15,000-ton system at Mid America Energy Resources (Indianapolis), to \$35,000,000 for a 12,000-ton cooling system at Trigen-Kansas City. On a unit cost basis, this represents an installed system cost of between \$1400/ton and \$2900/ton.

In order to provide commonality for a comparison between the DC and LDC systems, the comparison was based on the cost of producing a given conditioned airflow. LDC systems directly process a specific volume of conditioned air, so their specific costs (dollars per cfm) can be calculated directly. District cooling systems directly produce only chilled water; a separate air handling component actually produces the chilled air. Consequently, calculation of the specific cost (dollars per cfm) for district chilled water systems and LDC systems can be done only if the operating conditions of the associated air handling component are known. For the purposes of this cost study, it was assumed that an industry average of 400 cfm of conditioned air can be produced per ton of chilled water. Accordingly, the fixed cost component of a modern district chilled water (DC) system ranges between \$3.78/cfm and \$7.29/cfm.

Equipment and installation costs were provided by Kathabar Systems for a typical commercially available liquid desiccant cooling system. The LDC systems were chosen to be suitable for use with low-temperature (200°F) hot water. Table 5.1 details that these installed system costs range between \$70,200 for a 1500-cfm unit to \$350,000 for a 100,000-cfm unit. On a specific cost basis, this translates into a fixed cost of between \$46.80/cfm for a very small unit to \$3.50/cfm for a very large system.

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TABLE 5.1
EXISTING LDC SYSTEM COSTS

Air Volume (scfm)	Equipment Cost	Installation Cost	Installed Cost	Cost/cfm
1,500	\$ 46,800	\$23,400	\$ 70,200	\$46.80
4,000	\$ 58,700	\$26,415	\$ 85,115	\$21.28
12,000	\$ 84,000	\$29,400	\$113,400	\$ 9.45
25,000	\$120,000	\$36,000	\$156,000	\$ 6.24
50,000	\$185,700	\$55,710	\$241,410	\$ 4.83
100,000	\$280,000	\$70,000	\$350,000	\$ 3.50

Figure 5.1 shows a comparison of existing DC and LDC system installed costs. This figure illustrates that the installed cost of existing large (over 25,000 scfm) LDC cooling systems falls within the range of typical DC system installed costs. Any installed cost premium that large LDC equipment has is comparable to the cost premium of a modern district chilled water system. Consequently, depending on the variable (energy) costs of providing the desiccant cooling, existing LDC systems may represent an economical cooling alternative. In fact, Chapter 4 of this report shows that the total cost of large existing desiccant cooling systems is at the low end of existing district chilled water costs.

Although they comprise a limited market, these large DHC customers would represent a valuable summertime load for DH energy suppliers. Furthermore, combined district heating/cooling companies could expand the capacity of their existing chilled water system by adding desiccant cooling to their customers' portfolio of energy options. These combined DHC systems would not have to add additional central chillers or chilled water distribution capacity.

Alternatively, district heating suppliers who are planning to add district cooling systems could minimize their DC system installed costs and combine heat-actuated LDC cooling equipment with customer-based heat-actuated absorption chillers, or centrally-supplied chilled water.

Finally, DH systems operators may have other reasons to consider using existing LDC equipment. The St. Louis case study discussed previously in this report involves a site-specific case: a customer requires additional moisture removal capability due to a lack of mechanical cooling capacity. This St. Louis customer requires independent control of dry bulb temperature and humidity. Other reasons to use existing LDC equipment include using the biocidal capabilities of LiCl-based cooling systems, or using them to improve indoor air quality through increased usage of fresh air.

5.2 PREDICTED LEVEL OF COST REDUCTION

The goal of this task was to thoroughly review the state-of-the-art of liquid-desiccant cooling systems and components. The objective of this review was to examine which system components could be made less expensive through careful selection of materials, or by substituting commercially available components such as valves, pumps, and heat exchangers, etc. In particular, redesign of desiccant components was examined to reflect their intended specific use in lower temperature district heating system applications.

Figure 5.1 Suitability of Existing LDC Equipment in District Cooling Applications

The largest potential equipment savings were expected to involve replacing the existing custom-designed low-volume LDC conditioner and regenerator components with low-cost analogs from the closely related cooling tower industry. The main design criteria of cooling towers are similar to those of liquid desiccant systems; that is, spreading a liquid over a large surface area in order to allow good liquid/air contact while minimizing parasitic energy usage. In order to use an existing cooling tower design in a low-cost liquid desiccant cooling system, an acceptable cooling tower needed to be selected and any necessary modifications determined, based on the slight differences between the units.

An electronic literature search was performed using the Dialog literature search service in File 535: Thomas Register Online. This search was conducted to reveal existing manufacturers of plastic (or non-metallic) cooling towers, who could provide systems with exterior shell designs that would be easily modifiable for low-cost liquid desiccant cooling systems. Search results revealed that there are 37 unique manufacturers of cooling towers that use plastic or non-metallic materials as their primary materials of construction. A screening of these manufacturers resulted in the identification of a number of potential suppliers. The candidate cooling tower exterior shell designs are based on:

- Pultruded fiberglass reinforced plastic (FRP) double-wall structural panels that can be assembled into the required tower configuration through the use of a variety of interlocking watertight and airtight edge connections;
- Rotationally molded plastic, usually polyethylene, that can be molded as a single piece for smaller cooling towers, or as a section of larger towers;
- Hand-made FRP structural units that involve shop fabrication of manually applied fiberglass and plastic resin.

The physical size of all these candidate shell designs was determined to be suitable for the range of LDC systems under consideration. Furthermore, all these shell designs were seen as suitable for the intended application. Use of any of these alternative construction techniques was seen as a method of significantly reducing the labor intensity and unit production cost of LDC equipment. Estimations were made of the mechanical modifications and costs necessary for conversion of these water-based cooling units to liquid desiccant-based cooling systems. Modifications included the addition of plastic fans, where appropriate, and revised fill and mist eliminator materials.

Once the analysis of the LDC system's conditioner and regenerator was complete, the cost reduction potential in the remaining system components was investigated. The major remaining components that were studied included the liquid desiccant cooling heat exchanger, liquid desiccant heating heat exchanger, liquid desiccant solution pumps, controls, and installation materials and labor. These components are generally custom-engineered, then special-ordered for each individual LDC system. An initial investigation looked at cost reductions produced by replacing these high-cost special-order components with alternative low-cost components.

In particular, no alternative low-cost options were uncovered for several of these items. These components included the cooling and heating heat exchangers, controls, and the installation materials and labor. No large plastic-based heat exchangers exist to replace the titanium plate-and-frame units that are used currently. However, the commodity cost of titanium has been dropping in recent years due to current supply and demand conditions. This expanding supply condition for titanium is expected to continue for the next several years. Consequently, further moderate decreases in the cost of titanium plate-and-frame heat exchanger costs would be expected.

Although the control system has already been value-engineered by existing LDC equipment suppliers, minor savings were seen as possible in the system controls area. Unfortunately, as the simple unit controls used currently do not represent a major fraction of the total equipment cost, the cost savings are modest.

Moderate savings would be possible in the area of solution pumps. There are all-plastic or plastic-coated pumps commercially available today that represent an improvement in value. However, as the two solution pumps comprise only a tiny fraction of the system's total cost, the resultant savings represent only a minor reduction in system overall costs.

Table 5.1 illustrates that installation material and labor costs represent approximately 25 percent to 50 percent of the LDC equipment costs. These costs are fairly inelastic, and where possible have already been minimized. For example, it is not possible to have the LDC equipment manufacturer provide additional shop-packaging of the systems. The modular LDC equipment is pre-assembled where possible, and must occasionally be disassembled for shipping purposes. Furthermore, as rigging, piping, wiring, and ductwork must be considered separately for every individual installation, there is little that the LDC equipment supplier can do to reduce these costs by pre-packaging. For example, other vendors already market quick-assembling ductwork, which does prove economical in some locations. Only a ten-percent savings was seen as possible for these installation costs.

The cumulative cost-reducing effect of these LDC alternatives was found to be modest, as LDC equipment manufacturers have had several decades to value-engineer their existing industrial-duty products. These existing LDC products perform well in their intended industrial-type markets. However, applying such industrial-grade LDC equipment to the heating, ventilating, and air-conditioning (HVAC) market will not result in a major market penetration. Such expanded unit sales require a lower-cost commodity-type product. Tecogen's experience is that such cost reduction possibilities can often be expected to result when changing from a custom-engineered industrial-grade product to a mass-produced lighter-duty product.

Of course, annual unit volumes of several thousand units would be required in order to justify tooling up for production of an HVAC-grade LDC product. Such evidence of large annual unit volumes is detailed in the market study presented later in this report. These marketing results estimate that a thirty-fold increase in US LDC equipment unit sales is easily achievable, raising total LDC system annual shipments from 150 units to 5093 units.

Annual production volumes of five thousand LDC systems would certainly afford numerous production efficiencies to be implemented. These efficiencies would include:

- Reduced costs on existing in-house-produced components, resulting from the lower cost (automated) manufacturing procedures that would apply to the larger production volumes;
- Improved production planning, increased efficiency, improved quality, and reduced costs due to moving a larger portion of the manufacturing process in-house;
- Better quantity discounts on purchased raw materials;
- Larger-volume OEM discounts on those components that must still be purchased from outside suppliers; and
- Marked economies due to better amortization of fixed, selling, and general and administrative costs across a significantly increased revenue base.

An engineering estimate was made of the cost effect of these several volume-based efficiencies. Results included an assessment that materials form a larger fraction of system cost in the larger equipment sizes. Furthermore, lower levels of

cost reduction would be expected in the larger equipment sizes, as there was a lower labor content in these larger flow capacities. Table 5.2 summarizes the expected 25 percent to 50 percent level of cost reduction attributable to the expected level of low-cost LDC equipment production.

Table 5.3 details the total costs resulting from implementing the equipment and installation savings attributable to the new high-volume design. The total installed cost of a small 1500-cfm LDC unit has been reduced from \$70,200 to \$44,460. On a very large 100,000-cfm LDC system, savings of \$77,000 result in a reduced-cost system price of \$273,000. Specific costs range from \$2.73/cfm for a large LDC system to \$29.64/cfm for a small system.

Figure 5.2 illustrates a comparison of this reduced-cost LDC equipment with the installed cost of alternative DC systems. The installed capital cost of the high-volume reduced-cost LDC equipment is shown to be competitive with the installed cost of conventional district chilled water systems over a wider range of LDC system sizes. The capital cost of conventional DC systems is preferable only when the LDC system conditioned air flowrate is reduced below 10,000 scfm.

5.3 COST REDUCTION STUDY CONCLUSIONS

Today's LDC equipment is relatively expensive due to limited production volume. A detailed examination was made aimed at reducing the cost of LDC equipment. This analysis revealed that potential equipment cost savings of 25 percent to 50 percent were possible. Efficiency-related savings due to potential large LDC system sales volume increases were the main reason leading to these savings. The installed cost of these low-cost LDC installations would be cost-competitive with DC-supplied chilled water equipment costs down to a size of 10,000 cfm.

TABLE 5.2
EXPECTED LEVELS OF COST REDUCTION

Air Volume (scfm)	Equipment Cost Reduction	Installation Cost Reduction
1,500	50%	10%
4,000	45%	10%
12,000	40%	10%
25,000	35%	10%
50,000	30%	10%
100,000	25%	10%

TABLE 5.3
ESTIMATED LOW-COST LDC SYSTEM COSTS

Air Volume (scfm)	Equipment Cost	Installation Cost	Installed Cost	Cost/cfm
1,500	\$ 23,400	\$21,060	\$ 44,460	\$29.64
4,000	\$ 32,285	\$23,774	\$ 56,059	\$14.01
12,000	\$ 50,400	\$26,460	\$ 76,860	\$ 6.41
25,000	\$ 78,000	\$32,400	\$110,400	\$ 4.42
50,000	\$129,990	\$50,139	\$180,129	\$ 3.60
100,000	\$210,000	\$63,000	\$273,000	\$ 2.73

Figure 5.2 Suitability of Reduced-Cost LDC Equipment in District Cooling Applications

6. MARKET STUDY OF HEAT-ACTUATED DESICCANT COOLING APPLICATIONS

This task determined the existing market potential for heat-actuated liquid desiccant cooling (LDC) equipment. This market study quantified the application of heat-actuated LDC systems to existing district heating (DH) systems as well as to the national comfort cooling market. In addition, the expected size distribution of LDC equipment was determined through a number of alternative measures.

Results from this market study were viewed to be essential for analysis of the candidate low-cost LDC system. Just as the installed costs resulting from the cost reduction study outlined above were required to perform an economic analysis in the four case studies, results from the market assessment impacted the LDC cost reduction study.

6.1 DHC MARKET SIZE

Information was gathered from the International District Heating and Cooling Association (IDHCA) "1988 District Heating and Cooling Industry Statistics Report." Highlights from this report, detailed in Tables 6.1, 6.2, and 6.3, state that:

- 92 separate member organizations responded to the IDHCA survey;
- These organizations reported 50,046 MMBtu/hr of total steam, hot water, and chilled water production capacity;
- This production capacity is served through 634.5 miles of supply pipe;
- Due to a low portion of condensate return piping on district steam systems, only 353.9 miles of return pipe are installed by these users; and
- 560,068,721 sq. ft. of building area are served by IDHCA member district steam, district hot water, or district chilled water.

Review of the 1988 Survey revealed that 65.2 percent of the survey respondents were not thermal utilities. Table 6.4 details that these 60 individual users contributed 38 percent of the 1988 survey's total district energy sales. Consequently, this showed that a significant non-utility district energy market exists, as there are certainly many more than 60 colleges, universities, and "other" organizations in the U.S.

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TABLE 6.1

SOURCE OF IDHCA STATISTICS

Number of Thermal Utilities Reporting	32
Number of Colleges and Universities	35
Number of "Other" Organizations	<u>25</u>
TOTAL	92

TABLE 6.2
SUMMARY IDHCA STATISTICS

Description	Production Capacity (MMBtu/hr)	Supply Pipe (Miles)	Return Pipe (Miles)	Building Area Served (Sq. Ft.)
District Steam Systems	41,182	479.7	205.9	362,146,820
District Hot Water Systems	3,919	72.8	73.0	81,564,211
District Chilled Water Systems	4,945	82	75	116,357,690
TOTAL	50,046.00	634.50	353.90	560,068,721.00

TABLE 6.3
SUMMARY IDHCA OPERATING DATA

	Annual Sales (MMBtu/yr)	Annual Load Factor (Assuming 8000 hr/yr Operation)
District Steam	51,118,901	15.5%
District Hot Water	3,431,139	11.0%
District Chilled Water	5,466,983	13.8%
Cogenerated Electricity (at 3413 Btu = 1 kW-hr)	5,601,942	Not Applicable
TOTAL	65,618,965	

TABLE 6.4
DISTRICT ENERGY SUPPLIED BY UTILITY
AND NON-UTILITY MEMBERS OF IDHCA

IDHCA Member Description	Number	Percentage of Total	Total Energy Sales (MMBtu/yr)	Percentage of Total	Energy Sales Per Member (MMBtu/yr)
Thermal Utilities	32	34.8%	40,683,868	62.0%	1,271,371
Colleges, Universities, and "Other" Organizations	60	65.2%	24,935,098	38.0%	415,585
TOTAL	92		65,618,966		

(From 1988 IDHCA District Heating and Cooling Survey)

With this as background, the Association of Physical Plant Administrators of Colleges and Universities (APPA) was contacted in order to gather additional non-utility DHC market information. The APPA provided information obtained in their 1990 International Experience Exchange (IEE). Table 6.5 outlines the makeup of the respondents to the 1990 IEE. Most striking is the observation that two-thirds of the APPA respondents possess cooling or cooling-and-heating plants. This can be contrasted to the much lower IDHCA figure in Table 6.2, where only 12-percent of the total installed capacity is chilled-water-based. It seems that by necessity, the institutional DHC market has added cooling capacity faster than the overall DHC community. In conclusion, there clearly is room for the balance of the DHC community to markedly expand their district cooling supply capabilities.

An estimate of the APPA membership's total annual energy sales can be made by assuming that the size of the average APPA member is comparable to the size of the average IDHCA member. Applying the 415,585 MMBtu/yr average energy sales per non-utility member of the IDHCA that is shown in Table 6.4 results in a total annual energy sales of 184,520,000 MMBtu/yr for the 444 APPA members. Comparatively, the APPA survey respondents may represent 3.4 times the heating and cooling market of the IDHCA.

The US Department of Energy, Energy Information Agency (EIA) performs a comprehensive survey of commercial building's energy consumption and expenditures every three years. Table 6.6 details the overall results of the 1986 survey relative to the DHC market. In particular, 5,026 million square feet of floor space, representing 8.6 percent of the total US commercial building stock, are supplied by DHC. The energy consumed by these district energy-supplied buildings totals 721 trillion Btu/yr, representing 14.4 percent of the total commercial building energy usage. Accordingly, district energy usage in 1986 represented one-seventh of the total used by commercial buildings.

Table 6.7 compares the above IDHCA and APPA survey results with the EIA survey results. The building area served by the IDHCA respondents represent 8.8-percent of the total US DHC market. The district energy used by the IDHCA respondents represents 12.9-percent of the total US DHC market. Additionally, the district energy estimated to be used by the APPA respondents represents 43.7-percent of the total US DHC market. In summary, over 56 percent of the total DHC energy used in the US is supplied by either the IDHCA or APPA survey respondents.

Being DHC energy users, and therefore perhaps more interested in efficient means of energy utilization, the membership and customers of the IDHCA and APPA clearly would be open to considering liquid desiccant cooling (LDC) systems.

TABLE 6.5
INSTITUTIONAL DISTRICT HEATING MARKET IN THE U.S.

Description	Measure	Percentage of Total
Heating Plants	146	32.9%
Cooling Plants	17	3.8%
Cooling and Heating Plants	281	63.3%
TOTAL MEMBERS	444	100.0%

**(From APPA, The Association of Physical Plant
Administrators of Colleges and Universities)**

TABLE 6.6
SIZE OF DISTRICT HEATING
MARKET IN THE U.S.

Description	Measure	Percentage of Total
Total Floorspace, All Buildings (Million sq. ft.)	58,229	
Total Floorspace, Buildings with District Heat (Million sq. ft.)	5,026	8.6%
Total Energy Consumed, All Buildings (Trillion Btu)	5,022	
Total Energy Consumed, Buildings with District Heat (Trillion Btu)	721	14.4%

**From U.S. Department of Energy Report
No. DOE/EIA-0318(86)**

TABLE 6.7
COMPARATIVE SIZE OF IDHCA, APPA, AND U.S. MARKETS

Description	Measure	Percentage of Total
District Heat Building Area (sq. ft.)		
IDHCA	443,711,031	8.8%
DOE EIA (Total U.S. DHC Market)	5,026,000,000	100.0%
District Heat Energy Used (MMBtu/yr)		
IDHCA	54,550,040	12.9%
APPA (Estimated)	184,520,000	43.7%
DOE EIA (Total U.S. DHC Market)	422,000,000	100.0%
TOTAL IDHCA MEMBERS	92	
TOTAL APPA MEMBERS	444	

(From IDHCA, The International District Heating and Cooling Association; APPA, The Association of Physical Plant Administrators; and DOE/EIA-0318(86))

Consequently, existing DHC system users can be seen to represent an almost captive market for LDC equipment. Future expansion of the existing DHC market would certainly expand the market for LDC equipment. However, the results detailed above demonstrate that the existing DHC market already represents quite a large, suitable niche market for LDC cooling equipment.

6.2 LDC EQUIPMENT MARKET SIZE

The previous subsection of this report details how large the existing DHC niche market is for LDC cooling equipment. This report subsection explores how large the potential overall LDC equipment market is.

Table 6.8 displays a summary of one small segment of the heating, ventilating, and air-conditioning (HVAC) equipment market, as reported by members of the American Refrigeration Institute (ARI). A total of 49,393 air handling units were supplied in 1988 by the ARI members, representing \$206 million in sales. These air handling systems would be used to produce hot and/or cold conditioned air, using coils supplied with either building-generated steam, district chilled water, or other forms of energy. Consequently, at least half of these 49,393 air handling units represent installations that potentially could use LDC equipment for dehumidification purposes.

Also shown in Table 6.8 is the calculated average unit cost of these air handling units. On a number-weighted average basis, the average per-unit equipment cost is \$0.49/cfm. This shows that the customer-based air handling equipment cost component of conventional DH or DC systems is only a small fraction of the \$3/cfm to \$7/cfm installed equipment cost typical of central district chilled water systems. This emphasizes that the DHC energy supplier would be the most likely purchaser of the customer-based LDC equipment, as DHC suppliers have historically been ready to assume the major capital costs associated with space conditioning equipment.

A more representative cross section of the US HVAC market is shown in Table 6.9, which contains nationwide sales information extracted from the US Department of Commerce Report Number MA35M(89)-1. This table details that in recent years, between 573,245 and 595,176 room fan-coil and central station air handling units have been sold. Again, as with the ARI data, many of these units could effectively incorporate LDC equipment for dehumidification and cooling purposes. For the purposes of this study, it was assumed that each of these half-million units represents a potential LDC system sale. Not all of these potential sales would result in an LDC system sale, however. Total LDC system sales would be estimated based on how many potential LDC system sales in each market segment result in an actual system sale, or the cumulative LDC market penetration.

TABLE 6.8

**U.S. HVAC MARKET – EQUIPMENT SIZE DISTRIBUTION
(1988 ARI MEMBER SALES OF AIR HANDLING UNITS)**

Size, as Coil Face Area (sq. ft.)	Number of Units	Total Value (\$MM)	Unit Cost (\$/Unit)	Average Assumed Size (cfm/Unit)	Average Unit Cost (\$/cfm)
Under 3	2,140	\$ 2.5	\$ 1,168	1,000	\$1.17
3.1 to 5	4,700	\$ 6.2	\$ 1,319	2,025	\$0.65
5.1 to 10	14,631	\$ 32.2	\$ 2,201	3,775	\$0.58
10.1 to 15	8,388	\$ 26.2	\$ 3,124	6,275	\$0.50
15.1 to 20	4,959	\$ 20.0	\$ 4,033	8,775	\$0.46
20.1 to 30	6,503	\$ 35.2	\$ 5,413	12,525	\$0.43
30.1 to 40	4,366	\$ 33.9	\$ 7,765	17,525	\$0.44
40.1 to 50	2,428	\$ 28.1	\$11,573	22,525	\$0.51
Over 50	1,278	\$ 21.7	\$16,980	37,500	\$0.45
Totals	49,393	\$206.0			
Number-Weighted Average			\$ 4,171	8,577	\$0.49

Source: American Refrigeration Institute

TABLE 6.9
U.S. HVAC MARKET – EQUIPMENT SALES

Product Description	1989	1988
	Quantity	Quantity
Room Fan-Coil Air-Conditioning Units	264,474	254,778
Central Station Air-Handling Units	308,771	340,398
TOTAL	573,245	595,176

(From U.S. Department of Commerce Report No. MA35M(89)-1)

The same Department of Commerce report summarizes closed-cycle and open-cycle absorption refrigeration and dehydration systems sales, as shown in Table 6.10. Unfortunately, only summary sales data are made available in order to avoid disclosing figures for the limited number of individual companies surveyed. Specifically, between 748 and 880 liquid-desiccant, solid-desiccant, single-effect absorption chillers, and double-effect absorption chiller machines have been shipped in recent years. This can be contrasted with the hundreds of thousands of fan-coil and air handling units shown in Table 6.9 – total absorption system sales represent only about 0.1 percent of the air handling unit sales.

An estimate of the existing liquid desiccant equipment market can be made, assuming that 20 percent of the total absorption system sales represent open-cycle LDC equipment. This results in a current LDC market size of 150 systems annually. Obviously, this limited sales volume must be contributing to the current relatively high cost of LDC equipment. Furthermore, such low annual unit volumes imply that large production efficiency gains may potentially exist. However, in order to calculate the potential cost reduction, the likely sales volume increase for LDC systems needs to be calculated.

Table 6.11 details one such calculation of the potential annual increase in LDC equipment sales. Initially, the total annual HVAC system sales figures of Table 6.9, representing the total number of potential LDC system sales, are divided into two separate markets. These markets are the building floor space served by DHC and the building area not served by DHC suppliers. The resultant potential annual sales are 49,479 units to buildings with DHC, and 523,766 units to non-DHC buildings.

The next step is to estimate the realistic level of market penetration that could be realized in these two distinct markets. Previously, this study identified factors that identified the DHC market as being more amenable to efficient energy conversion methods. Consequently, it was assumed that the potential market penetration for the DHC buildings would be a factor of ten greater than for the non-DHC buildings: 5-percent penetration for DHC buildings, and 0.5 percent for non-DHC buildings. Applying these penetration figures to the two potential markets produced an estimate of 2,474 annual LDC system sales to buildings served by DHC, and 2,619 annual LDC system sales to buildings that are not served by DHC. The predicted level of 5,093 annual units represents a 3304 percent increase over the existing level of 150 annual LDC system shipments.

Such a potential thirty-fold increase in potential LDC system sales should certainly excite manufacturers of these systems. In fact, the potential sixteen-fold increase in LDC system sales to only the DHC market segment should be enough

TABLE 6.10

U.S. HVAC MARKET – LIQUID DESICCANT EQUIPMENT SALES

Product Description	1989			1988		
	Quantity	Value (X1000)	Average Value	Quantity	Value (X1000)	Average Value
Absorption Refrigeration and Dehydration Systems	748	\$35,607	\$47,603	880	\$30,901	\$35,115
Assumed Liquid Desiccant System Sales (at 20 Percent of Above)	150	\$ 7,121	\$47,603	176	\$ 6,180	\$35,115

(From U.S. Department of Commerce Report No. MA35M(89)-1)

TABLE 6.11
POTENTIAL ANNUAL U.S. LIQUID DESICCANT
COOLING EQUIPMENT SALES

Product Description	HVAC Equipment Quantity	Potential LDC Sales Penetration	Liquid Desiccant Equipment Quantity
Total Annual HVAC System Sales (Quantity) (From Table 6.9)	573,245		
Sales to Building Floorspace With DHC (at 8.6 Percent of Above) (From Table 6.6)	49,479	5%	2,474
Sales to Building Floorspace Floorspace Without DHC	523,766	0.5%	2,619
Total Potential Annual LDC System Sales			5,093
Calculated Current LDC System Sales (From Table 6.10)			150
Total Potential Annual Unit Increase for LDC System Sales			4,943
Potential Annual Increase in LDC Equipment Sales			3304%

to stimulate a manufacturer's interest. Other chapters of this report discuss the equipment, installation, and operating cost implications associated with this increase in production volume, and how the total cost of LDC systems becomes quite attractive.

6.3 MARKET STUDY CONCLUSIONS

The US LDC equipment market was divided into two distinct segments during the course of this study. The market segments involve buildings using district energy and those buildings which do not use district energy. The DHC market segment represents 8.6 percent of the total commercial building market, or 14.4 percent of the total energy consumption of the commercial market. As those in the DHC market segment have actively examined and chosen their source of heating and cooling energy, these buildings' operators would obviously be more interested in examining and using an alternative, desiccant-based means of cooling than the non-DHC segment.

The existing US LDC equipment market was determined to represent 150 annual sales, as compared to conventional cooling equipment sales levels exceeding half a million units annually. A conservative increase in annual LDC equipment sales was calculated, assuming that a significantly reduced installed cost would lead to 5-percent market penetration in the DHC market and 0.5-percent penetration in the non-DHC market. The resultant LDC system annual sales volume increase is 3304 percent, to a new level of 5,093 annual units.

Such increased production levels would certainly lead to marked decreases in LDC system production cost. Other chapters of this report discuss these equipment cost savings, as well as the installation and operating cost implications, and how the total cost of LDC systems becomes quite attractive.

7. CONCLUSIONS AND RECOMMENDATIONS

An assessment of the use of desiccant-based customer-sited heat-actuated cooling for District Heating and Cooling (DHC) systems has been completed. This assessment had three principal components: a market study of existing and future reduced-cost liquid desiccant cooling (LDC) systems; an examination of the installed costs of these existing and reduced-cost LDC systems; and four detailed case studies. The installed costs of the two designs of LDC equipment were compared to existing district cooling (DC) system capital costs that ranged between \$3/cfm and \$7/cfm. The case studies compared the equivalent chilled water cost of the two versions of LDC cooling systems to district chilled water that ranged from a low of \$0.15/ton-hour to a high of \$0.30/ton-hr.

In the market study, the US LDC equipment market was divided into two distinct segments. The market segments involved buildings using district energy and those buildings which do not use district energy. The DHC market segment represented 8.6 percent of the total commercial building market, or 14.4 percent of the total energy consumption of the commercial market. Compared to the non-DHC segment, the DHC market segment was found to be more interested in examining and using an alternative desiccant-based means of cooling.

The existing US LDC equipment market was determined to represent 150 annual sales, as compared to conventional cooling equipment sales levels exceeding half a million units annually. A conservative increase in annual LDC equipment sales was calculated, assuming that a significantly reduced installed cost would lead to 5-percent market penetration in the DHC market and 0.5-percent penetration in the non-DHC market. The resultant LDC system annual sales volume increase was 3304 percent, to a new level of 5,093 annual units.

A cost analysis showed that in large size ranges (above 25,000 cfm) the capital cost of existing LDC equipment is quite competitive with the capital cost of conventional district chilled water systems. A detailed examination was made of a cost-reduced high-volume design for LDC equipment. This analysis revealed that a potential equipment cost savings of 25 percent to 50 percent was possible due to production volume and efficiency-related savings. The installed cost of these future low-cost LDC installations would be cost-competitive with DC-supplied chilled water equipment costs down to a size of 10,000 cfm.

Case study design data for four geographically distinct sites were gathered. These sites were located in the service area of District Energy St. Paul (Minnesota), Toronto District Heating Corporation (Ontario, Canada), Boston Thermal Energy Corporation (Massachusetts), and St. Louis Thermal Energy (Missouri).

LDC cooling systems under consideration ranged from a 6000-scfm unit at St. Paul to an 80,000-scfm installation at St. Louis.

Only moderate differences in the instantaneous design cooling load were observed between the four sites. Consequently, one design style of LDC equipment was found to satisfy a specific cooling application in any of the four temperate locations. However, major differences were established between the seasonal cumulative cooling energy usage of the four sites – for a particular application, 2.4 times the seasonal cooling energy usage was found to be required in St. Louis, compared to Toronto. It was found that there is a need for a modified form of simple dry-bulb-based cooling degree days, which would allow for estimation of humidity (latent cooling) effects on energy consumption.

An economic analysis was completed for each site, comparing conventional centrally-supplied district chilled water to customer-sited district-heat-actuated LDC equipment. The LDC analyses included computations of variable (energy) costs as well as fixed (capital) costs for both existing and reduced-cost LDC equipment. Hourly operating costs for the LDC equipment varied between \$3.02/hr at St. Paul to a maximum of \$57.34/hr at St. Louis. Corresponding annual variable costs ranged between \$8,636/yr and \$270,830. Installed system costs for the existing LDC equipment ranged between \$90,000 for the 6,000-scfm St. Paul installation to \$313,000 for the 80,000-scfm unit at St. Louis. Corresponding installed system costs for the reduced-cost LDC equipment ranged between \$59,000 and \$240,000.

These variable and fixed costs were expressed on a cost-per-ton-hour basis and compared to current district chilled water costs. The total cooling cost of large, currently produced LDC systems was determined to be slightly below low-cost 15 cents/ton-hour district chilled water. Future low-cost moderate- and large-sized LDC systems would produce cooling at a cost that is 3 cents/ton-hr lower than current low-cost district chilled water. Thus, existing large liquid desiccant cooling systems are economical in today's DHC environment; a reduced-cost LDC design would extend the economic range of this technology to much smaller sizes.

In conclusion, district energy system operators and building owners and operators would consider using LDC equipment if its total cost was less than conventional 15 to 30 cents/ton-hour chilled water delivery, or if there were other overriding tangible benefits. This report discusses the tangible advantages of using LDC equipment, such as its efficiency, its ability to provide independent humidity and temperature control to conditioned spaces, the fact that it does not use CFC (chlorinated fluorocarbon) working fluids, and its biocidal and virucidal (air purification) characteristics. This report also shows that the cost of existing large

LDC installations is comparable to 15 cents/ton-hr chilled water. Consequently, because LDC systems do not use CFCs and because of their other tangible benefits, existing LDC systems are more attractive to DHC users.

As a result of this program's positive results, it is recommended that LDC cooling technology be made more accessible to the DHC community. This could be implemented through:

- A hardware installation of existing LDC equipment at a DH user site, in order to demonstrate the numerous benefits of existing LDC systems,
- Marketing assistance and technology transfer to the DHC community, in order that they more fully understand the use and benefits of LDC systems; and
- Interesting a manufacturer in producing the high-volume low-cost LDC systems discussed in this report, so that they may make an important contribution to the heat-actuated cooling market.

A trend towards increasing worldwide-levels of DHC is emerging. Heat-actuated cooling will certainly play a major role in this development. By making LDC technology more accessible to the DHC community, desiccant cooling will be able to take its place among the range of heat-actuated cooling options.

8. REFERENCES

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