# THE PERFORMANCE OF GEOTHERMAL HEAT PUMPS IN ENERGY-EFFICIENT HOMES

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## ABSTRACT

*In 1993 a Massachusetts power company began a pilot program to pay incentives to builders who installed geothermal heat pumps (GHP) into energy-efficient homes they were building. The premise of this pilot was to install high-efficiency heating and cooling systems in homes with good thermal envelopes. The pilot also was an effort to reduce heating energy consumption by more than 70% compared to the State of Massachusetts code. The pilot was integrated fully as an incentive program within the power company's service territory in 1994. Since December 1993, metering has been installed in seven single-family homes with the following characteristics:*

*Closed-loop systems*

- *one energy-efficient home with a GHP, horizontal loop, and propane hot water;*
- *one energy-efficient home with a GHP, vertical loop, and propane hot water; and*
- *three energy-efficient homes with a GHP with a desuperheater, horizontal loop, and electric hot water.*

*Open-loop systems*

- *one energy-efficient home with a GHP with a desuperheater, using a domestic water well and electric hot water; and*
- *one energy-efficient home with a GHP using a domestic water well and hot water produced on demand by the GHP.*

*Metering currently is on the heat pump compressor, fan and auxiliary-resistance heat circuit, and electric domestic hot water. Meters are read by the customers and the information is sent to the power company through response cards. Some sites also monitor indoor and outdoor temperatures. Meters are read either daily, weekly, or monthly. Of primary interest was the total energy used for heating. A rough comparison of the actual energy consumption compared to the estimated energy consumption was obtained. The total energy extracted from the ground was not metered, so the actual system coefficient of performance (COP) could not be calculated.*

*Metering has shown performance to be close to what was predicted by simplified computer modeling and calculations using Air-Conditioning and Refrigeration Institute (ARI) ratings on the GHP systems. Further analysis is ongoing to benchmark these data against disaggregated billing data from non-energy-efficient, electric-resistance homes in the power company's service territory.*


## PROGRAM BACKGROUND

The energy efficient construction program was developed in 1989 and 1990 as a joint effort between several New England electric utilities to develop a demand-side management program to capture lost opportunities in the residential electric heat market. Initial review of many programs from the United States and Canada indicated that none fits the specific needs of the sponsoring utilities, and a decision to develop a new program was made. Based on knowledge gained through trade allies, state-of-the-art research, and similar performance-based conservation programs, the sponsoring utilities approved, in concept, a "house as a system" approach to the program design, recognizing that energy-efficient housing must tackle many other issues, such as moisture control and indoor air quality (IAQ). It is only when these other seemingly "non-energy" issues are addressed that the longevity of the thermal envelope and the well-being of the occupants are assured. The program was designed as a fuel-neutral program; however, incentives currently are paid for compliance only in electrically heated homes.

The goal of the program is to induce builders of electrically heated homes to incorporate thermal shell improvements that reduce heating energy consumption by 30% or more compared to the current Massachusetts state code requirements. This is achieved through builder training, computer evaluation of plans prior to construction, and construction techniques that incorporate high levels of insulation, airtight construction (blower door tested), and continuous mechanical ventilation. Builders receive incentives for meeting program specifications. Other electric end uses are targeted through the program, including lighting and water heating. Incentive schedules vary among the different utilities, in response to different regulatory controls and the

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level of inducement needed by builders in different areas to participate. In the power company's territory, incentives for shell improvements, lighting, water heating, and GHPs are as follows:

Shell: $1,000 + $1 per ft$^2$ of above-grade conditioned floor area.

Lighting: $25 per hard-wired compact fluorescent fixture in high-use areas. Fixtures must be thermally protected, with a power factor > 90% and total harmonic distortion < 20%.

Water heating: $1,300 for ventilating heat-pump water heaters. Incentives for stand-alone heat-pump water heaters and GHP water-heating functionality are being investigated.

GHP: Incentives are paid based on the ARI-rated efficiency of the GHP and the nominal tonnage, with higher incentives available for equipment of higher efficiency.

| COP | $/Ton | COP | $/Ton | COP | $/Ton |
|---|---|---|---|---|---|
| 2.9 | $1,188 | 3.3 | $1,495 | 3.7 | $1,755 |
| 3.0 | $1,250 | 3.4 | $1,560 | 3.8 | $1,820 |
| 3.1 | $1,313 | 3.5 | $1,625 | 3.9 | $1,885 |
| 3.2 | $1,430 | 3.6 | $1,690 | 4.0 | $1,950 |

Program implementation began in 1991, with two-day training for builders, one-day training for ventilation-system installers, and general marketing of the program. Implementation has continued to date, with one of the original sponsors discontinuing program sponsorship in its territories and other utilities beginning sponsorship. The sponsoring utility that discontinued the program did so due to a low penetration of electric heat in its new construction marketplace and, as a result, the program was not cost effective to run. Currently, the program is run in all or parts of Connecticut, Massachusetts, New Hampshire, and Rhode Island.

## BUILDER PROCESS

To participate in the program, a builder must first attend a two-day training course. Once completed, the builder may submit plans for a computer evaluation. The annual energy use for heating and cooling is estimated using a computerized energy modeling program. Every home that participates in the program is modeled prior to construction to establish eligibility. Features of the home that are evaluated during this modeling include the insulation values of all thermal-shell components, air leakage, mechanical ventilation, solar gains, thermal mass, simplified internal gains, conductive duct losses, and passive and active solar strategies. Once the home meets a building performance index (BPI) of 1.45 Btu/ft$^2$ of shell area/degree-day (1.45 Btu/SFS/DD) for heating, regardless of climatic zone, and a BPI of 2.75 to 3.75 Btu/SFS/DD for cooling (cooling BPI varies and is based on cooling DD) and the builder agrees to meet all other energy-efficient home standards, construction begins. During construction, a minimum of three inspections are performed, including visual inspection of the insulation and air sealing, blower door testing for a maximum effective leakage area (ELA) of 1 in.$^2$/100 ft$^2$ of shell area or less, and airflow cfm verification of the ventilation system. Upon successful completion of all inspections, the home is certified as energy efficient.

## THERMAL CHARACTERISTICS OF AN ENERGY-EFFICIENT HOME

The thermal characteristics of the program are based on performance standards, which allows builders the maximum flexibility to meet program requirements and encourages innovation toward cost-effective solutions. Performance standards were developed in four main categories—thermal performance, moisture control, indoor air quality, and heating and cooling systems.

The BPI of 1.45 Btu/SFS/HDD for heating and a BPI of 2.75 to 3.75 Btu/SFS/CDD for cooling normalize the impact of larger vs. smaller homes and further allow for similar relative performance among varying climatic zones. New England climates vary from about 5,600 to more than 8,000 heating degree-days and about 350 to 700 cooling degree-days. The cooling BPI varies to account for the low number of cooling degree-days and to account for the variability in New England cooling climates (shoreline to mountains). Builders may trade off any of the evaluated components to meet the respective BPIs, except for the airtightness standard and the ventilation flow rates. There are no absolute minimum insulation values for any component; however, higher insulation levels on all components are encouraged to help ensure not only energy efficiency, but to minimize condensation problems and to ensure comfort for the occupant. Builders may incorporate such strategies as superinsulation, passive or active solar, heat recovery ventilation, or propose other techniques to meet the heating and cooling BPIs. Heating, cooling, and hot water equipment efficiencies may not be used to trade off thermal envelope components, as the program was designed to minimize the thermal loads on the building itself, not simply to reduce purchased energy.

One of the most distinguishing characteristics of the program is the stringent airtightness standards that builders must meet. Airtight construction also helps to control moisture movement through the building envelope, which can contribute to longer effective life of the insulation and provide the occupant with fewer long-term moisture problems in the thermal shell of the building. Builders must meet a blower-door-tested ELA of 1 in.$^2$ or less per 100 ft$^2$ of shell area at a 4-Pa pressure difference. This is established by using a multipoint blower door test and interpolating the results to a 4-Pa pressure difference. This equates to approximately 0.15 to 0.22 average air changes per hour (ACH) under natural conditions. This performance testing is done on every energy-efficient home that participates in the program. Builders are becoming experienced with different airtight construction techniques, and it is not uncommon for homes to have ELAs of 0.25 to 0.5 in.$^2$ per 100 ft$^2$. Most builders are using an airtight polyethylene system, where the air barrier and the vapor barrier are one in the same for most of the house. Rim and band joists typically are sealed during framing with gaskets or caulk. Electric boxes are sealed with "poly pans" or other airtight electric boxes.

Indoor air quality is controlled in several ways. All energy-efficient homes must be equipped with spot and whole-house ventilation, which must be capable of continuous operation and have two speeds. Continuous ventilation must provide 15 cfm per person, based on 30 cfm for the first bedroom and 15 cfm for each additional bedroom. Spot ventilation must be provided in bathrooms and kitchens. These requirements allow for moisture and pollutant control in an airtight house, and many builders are incorporating such features as 24-hour timers to allow occupants to control ventilation periods. One problem with ventilation equipment is that most manufacturers rely on dampers to control low-speed (45 cfm to 75 cfm) operation. When ventilation systems are throttled down for continuous low-speed operation, high-speed operation typically suffers. Some manufacturers are now offering infinite variable-speed controls with their equipment, and some installers are wiring in solid-state controllers that can be jumped over by a boost switch. It is encouraging to see the advances being made in the ventilation field, as the quality and flexibility of systems are increasing as costs come down. It is estimated that a minimum ventilation system in an energy-efficient home can be installed for an incremental cost of about $300.

In addition to mechanical ventilation, the program has pollutant-source control specifications, which minimizes the potential impact of such source pollutants as radon, formaldehyde, and volatile organic compounds (VOCs).

While the combination of airtight construction and mechanical ventilation controls much of the moisture movement in an energy-efficient home, there are other specific moisture control requirements. Continuous vapor retarders, with not more than a 1-perm dry cup rating (ASTM n.d.), are required on all ceilings, walls, floors, and ducts that are insulated and exposed to unconditioned spaces or the outdoors. A 6-mil poly moisture barrier is required beneath all concrete floor slabs that are on earth and over all exposed earth in crawl spaces. Builders are taught how to control bulk and capillary moisture during builder training, including such details as providing a capillary break between footings and foundation walls.

Another requirement of the program is sealed combustion equipment. This includes such items as furnaces, boilers and domestic water heaters, and fireplaces and wood stoves. While this program was designed primarily for electric homes, the sponsoring utilities recognized the potential safety issues surrounding atmospherically vented equipment in airtight homes with mechanical ventilation. Requiring sealed combustion is seen as the best assurance that there would be no possibility of backdrafting in an energy-efficient home.

## TYPICAL AND ADVANCED THERMAL SHELL CONSTRUCTION TECHNIQUES

The following description is intended to provide an overview of the typical construction techniques incorporated into an energy-efficient home and to show how these minimums are exceeded by some program participants. An energy-efficient home that just meets program standards typically will have R-19 wall insulation, R-38 ceiling insulation, low-e gas-filled windows, insulated steel doors, and either R-30 insulation in the floors or R-13 insulation in the basement walls. Airtightness usually is achieved through an airtight poly system on insulated walls and ceilings, with band joists gasketed or caulked during framing. Simple exhaust-only ventilation systems are installed, with either a central fan unit or individual spot fans in the bathrooms and a range hood in the kitchen. The ventilation system typically has 24-hour control, and many are multispeed. Framing incorporates energy-efficient detailing, such as three-stud corners, insulated headers, and raised heel trusses. Many builders are now insulating with dense-packed cellulose and using loose-blown cellulose in attics. It generally is perceived that a dense-packed cellulose wall insulation system helps builders meet the energy-efficient home airtightness standards.

A smaller group of builders in the program is using thicker wall assemblies. The most common to date has been the "strapped" wall assembly. This consists of 2 × 6 studs at 24 in. o.c., with a 2 × 3 strap (on flat) at 16-in. o.c. installed horizontally on the stud wall. This allows for a 7-in. wall cavity with little thermal bridging. Some builders tried installing the 2 × 3 strap on its edge to get an 8-in. cavity, but the builders had shrinkage problems and difficulty nailing through the strap and were unable to get adequate holding. This system is insulated with dense-packed cellulose insulation, either installed after drywall or, more commonly, prior to drywall with netting or reinforced polyethylene holding in the cellulose. One difficulty experienced with this system is the "pillowing" of insulation, which can lead to bowing of the drywall or screw-head pops. Some builders have gone to 5/8-in. of drywall on these insulated walls; others are trying to get greater quality control in the insulation installation process.

Another innovative wall assembly that has been used is a modification on the standard double-stud wall. Using 2 × 8 or 2 × 10 top and bottom plates, 2 × 4 studs are installed at 24 in. o.c. on the outside of the wall and at 12 in. o.c. on the inside of the wall. This system also is insulated with dense-packed cellulose; however, the 12 in. o.c. stud spacing appears to have solved the pillowing problem. In addition, this system uses fewer board feet of lumber than the 2 × 6 strapped wall.

Another prevalent feature in energy-efficient home construction is full-basement wall insulation. One issue driving this decision is that many energy-efficient homes are being built with forced-air heating and cooling systems, and the relative cost difference between insulating the basement walls and insulating and air sealing all the ducts in the basement is nearly the same.

Air-sealing techniques range greatly from builder to builder. Some take great pains to seal as extensively as possible, integrating it into many phases of construction from framing to finish detailing. Others rely solely on an air-sealing contractor. As mentioned earlier, air sealing typically is done with an airtight poly system. Some builders rely extensively on dense-packed cellulose for airtightness in wall assemblies, with reasonable success. The airtight drywall approach (ADA) has not caught on in western Massachusetts; however, several builders have expressed interest in the concept and use some of the techniques in limited areas.

Ventilation systems in energy-efficient homes vary from fairly simple exhaust-only systems to more sophisticated heat-recovery ventilators (HRVs) and exhaust air heat pump (EAHP) water-heating systems. Utilities participating in the program are paying incentives for EAHPs, which is helping to introduce them into the market. Many builders are further evaluating the cost effectiveness of HRVs, based on the reduction of natural infiltration incurred by exhaust ventilation systems (ASHRAE 1993). Ductwork is air sealed to ensure ventilation air is drawn from the designated exhaust points, and efforts are made to educate the ventilation installer about proper fan location to minimize unwanted noise for the occupant.

A relatively new feature of many energy-efficient homes is the geothermal heat pump system for heating and cooling. A GHP uses earth energy to heat and cool a home and can provide up to 100% of the domestic hot water needs for the occupants. Most systems are being installed with closed-loop ground heat exchangers; however, some systems use ground water and one home uses surplus water from the public water supply. This town currently has a need to discharge approximately 20 gallons per minute from the water supply, and it allows the homeowner to run that water through the GHP system prior to going into a catch basin. GHP systems range in size from about 20,000 to 42,000 Btu/h heating and 28,000 to 61,000 Btu/h cooling (rated at ARI 330 [ARI n.d.] test conditions), with heating load sizing generally at about 10 to 15 Btu/ft$^2$ of above-grade conditioned floor area. Most GHP systems are sized for 100% of the load, with electric resistance installed as emergency heat, as opposed to auxiliary heat. Because of the energy-efficient home heating and cooling BPIs, the peak heating load, in general, closely matches the peak cooling load.

## PERFORMANCE FROM 1994 TO 1995

Of the sites mentioned earlier, four have yielded useful data. All of these sites have closed-loop GHPs, and sites 1, 2, and 3 are equipped with desuperheaters for domestic hot water production. The metered data for March 1994 to March 1995 are shown in Table 1. The initial premise of the metering was not for GHP system efficiency calculations, nor was it intended to be used as a validation of the modeling tool, but simply to get generic information on the end-use consumption of the GHP in these energy-efficient homes. As a result, either the ARI-rated heat pump efficiency or the energy estimates created by the modeling must be assumed as valid to calculate the in-place efficiency of the GHP or load on the building. Table 1 shows the estimated energy load from the computer model (accounting for weather and occupant thermostat setpoint during the metering period) and the estimated electric consumption for heating (at ARI 330-rated efficiency) and compares it to the metered consumption for each site. Tables 2 and 3 show the estimated heating load (based on computer modeling at average Hartford, CT, weather) if the

*TABLE 1* Modeled vs. Measured Energy Use

| Computer-Modeled Energy Estimates, Run with Similar Heating DD to 1994-1995 Season | | | | | | |
|---|---|---|---|---|---|---|
| Site | ARI 330 COP | Modeled Annual Heat Loss in MBtu | Measured Heating kWh Use | Predicted Heating kWh Use | Calculated COP | % Savings from Modeled Heat Loss |
| 1 | 3.3 | 47.9 | 4480 | 4253 | 3.1 | 70% |
| 2 | 3.6 | 44.8 | 4007 | 3646 | 3.3 | 72% |
| 3 | 3.6 | 43.0 | 3579 | 3500 | 3.5 | 72% |
| 4 | 3.4 | 75.2 | 7318 | 6480 | 3.0 | 71% |

*TABLE 2* **Energy Savings from GHP Then Energy Efficient Home Shell Improvements**

| Computer-Modeled Energy Estimates, Hartford, CT, Weather | | | | | | | |
|---|---|---|---|---|---|---|---|
| Site | Code Heat Loss (MBtu) | Code Resistance kWh Use | Code GHP COP | Code W/GHP kWh Use | kWh Savings from GHP | Energy Efficient Home W/GHP kWh Use | kWh Savings from Energy Efficient Home |
| 1 | 72 | 21096 | 3.5 | 6027 | 15068 | 4253 | 1774 |
| 2 | 71.2 | 20861 | 3.5 | 5960 | 14901 | 3646 | 2314 |
| 3 | 67.6 | 19807 | 3.5 | 5659 | 14148 | 3500 | 2159 |
| 4 | 108 | 31644 | 3.4 | 9307 | 22337 | 6480 | 2827 |

*TABLE 3* **Energy Savings from Energy Efficient Home Shell Improvements Then GHP**

| Computer-Modeled Energy Estimates, Hartford, CT, Weather | | | | | | | |
|---|---|---|---|---|---|---|---|
| Site | Code Heat Loss (MBtu) | Code Resistance kWh Use | Energy Efficient Home Heat Loss (MBtu) | Energy Efficient Home Resistance kWh | Energy Efficient Home kWh Savings | Energy Efficient Home W/GHP kWh Use | kWh Savings from GHP |
| 1 | 72 | 21096 | 53.1 | 15558 | 5538 | 6393 | 9165 |
| 2 | 71.2 | 20861 | 49.7 | 14562 | 6299 | 5796 | 8767 |
| 3 | 67.6 | 19807 | 48.4 | 14181 | 5626 | 5502 | 8679 |
| 4 | 108 | 31644 | 83.1 | 24348 | 7296 | 9307 | 15041 |

thermal envelopes of these houses were built to Massachusetts code minimums (similar to CABO MEC 1992) for electric resistance heat, and the estimated heating electric use for resistance heat and a GHP (assuming ARI 330-rated efficiency). Table 2 compares savings taken for the GHP first, then for the energy-efficient home shell. Table 3 shows the energy-efficient home savings taken before the GHP savings.

## CONCLUSIONS

Based on the metered data, it appears that the heat pumps are performing as expected in these homes, and that the shells of the buildings contribute to the low energy consumption for space heating. The actual heating energy use of these houses was reduced by 70% to 72% when compared to the estimated energy use at Massachusetts code construction levels with electric-resistance heat. When considering a GHP in an efficient shell, such as an energy-efficient home, the energy savings potential vs. the capital investment needed for installing the GHP might be questioned. Table 2 exhibits the estimated energy savings from installing a GHP in a code home. The estimated savings of using the energy-efficient home construction standards range from 1,063 kWh to 1,767 kWh, which, at first glance, appears to make little sense compared to the GHP savings of 13,143 kWh to 19,793 kWh. The issue that must be considered is the reduction in the GHP system size that the energy-efficient home shell affords to the total economics of the GHP system.

Shell improvements from code to an energy-efficient home typically cost from $1.20 to $1.40 per square foot of above-grade conditioned floor area, or about $1,700 to $4,000 per house. With this well-insulated shell, the GHP system in these examples can be downsized by about one ton, as shown in Table 4, depending on house size.

*TABLE 4* **Massachusetts Code vs. Energy Efficient Home—Peak Heat Loss**

| Site | Code Peak Heat Loss (kBtu) | Energy Efficient Home Peak Heat Loss (kBtu) | kBtu Difference |
|---|---|---|---|
| 1 | 36.3 | 26.5 | 9.8 |
| 2 | 36.1 | 25.1 | 11.0 |
| 3 | 36.2 | 28.0 | 8.2 |
| 4 | 53.7 | 41.4 | 12.3 |

With an average installed cost in western Massachusetts for GHPs at about $4,000 to $4,500 per nominal ton, it is at least as cost effective to improve the shell and downsize the heat pump than to simply put the GHP into the less efficient shell. This strategy also provides the other non-energy benefits of building an energy-efficient home, such as draft-free construction, greater comfort, controlled indoor air quality, and moisture control, that currently are not required by most building codes. One must also consider the potential for higher than typical infiltration rates in a house built to code minimums with forced air, due to the potential pressure indifference caused by an improperly designed and installed heating system.

These data are now being processed to more fully normalize for weather and occupant behavior. The metered data will then be compared to disaggregated billing data from electric-resistance homes built to code minimums.

It also should be noted that when a consumer does not require air conditioning, a GHP is not necessarily the best option, because it is a heating and cooling device. Another issue to consider is the production of hot water. Most GHP equipment can have a desuperheater for domestic hot water (DHW) production during heating and cooling; however, as the shell becomes more efficient, GHP runtimes decrease and the relative contribution of the desuperheater becomes smaller and smaller. Triple-function heat pumps that provide heating, cooling, and domestic hot water on demand can help solve this problem and maximize the higher investment in the GHP system. Other equipment that currently is being field tested by the power company is a stand-alone geothermal heat pump water heater as an add-on to existing GHP systems.

## FUTURE DIRECTIONS FOR THE PROGRAM

In 1995, members of the program are looking at the possibility of providing uniform home energy ratings as part of program delivery. This would be in conjunction with efforts to make preferential financing available to purchasers of energy-efficient homes, possibly using incentive payments as part of the down payment or to buy down interest rates. Ultimately, it is envisioned that the higher additional costs of the energy-efficient home and GHP will be financed by the customer, with utility incentives phased out over time. The power company is pursuing the idea that the net present value of the investment, not payback, should be used when presenting any energy upgrade option to residential consumers, assuming they are financing the upgrade. Under a net present value calculation, consumers typically are better off with energy-efficient homes, as the energy savings pay for or exceed the additional costs associated with financing the energy upgrades in the base mortgage. It remains to be seen whether these investments will pass through in future market transactions with higher resale values on these homes.

Sponsors of the program also are discussing cooperative participation with the Environmental Protection Agency's Energy Star Home program, a voluntary program intended to have homes built at least 30% more energy efficient than CABO MEC, in an effort to reduce air emissions from newly built homes in the United States.

## REFERENCES


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