ORNL/CON-462

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1. INTRODUCTION

The U.S. Army and a private energy service company are developing a comprehensive energy efficiency project to upgrade the family housing at Fort Polk, Louisiana. The project includes converting the space conditioning systems of more than 4000 housing units to geothermal (or ground-source) heat pumps (GHPs). This interim report describes the methodology of the evaluation associated with this project, including the field monitoring that has been conducted at the base.

1.1 BACKGROUND

The Strategic Environmental Research and Development Program (SERDP) was created by the National Defense Authorization Act of 1990 to address the long-term energy and environmental concerns of DOD. Funds for the SERDP program are authorized in six thrust areas, specifically clean-up, compliance, conservation, energy conservation/renewable energy, global environmental change, and pollution prevention.

One of the primary objectives of the energy conservation/renewable energy thrust area is to promote the demonstration of GHPs by DOD. DOD is the single largest consumer of electricity in the United States, and the costs of heating, cooling, and water heating in its facilities make up about one quarter of its total annual electricity budget. GHPs can potentially reduce electricity costs as well as maintenance costs. This project will help establish to what extent these savings materialize at Fort Polk.

Even after energy and maintenance cost savings are proven, major impediments to the use of GHPs by DOD will remain. Facility managers are generally unaware of the technology and its operating characteristics, and there is a lack of trained personnel to design, install, operate and maintain the equipment. These factors lead to difficulties in specifying and procuring equipment, and services such as installation and operation and maintenance (O&M), within the DOD procurement process. This project may contribute to overcoming these barriers as well.

DOD needs more confidence in methods to estimate the financial value created when GHPs are placed into service, and more confidence in GHP design and construction methods and O&M cost estimates, before it can prudently invest significant resources in in GHPs throughout its complex. The statistically valid data from Fort Polk will go a long way toward providing a foundation on which to build such confidence.

The Fort Polk demonstration opportunity exists because the U.S. Army and Co-Energy Group (a private energy service company, or ESCO) have entered into a shared energy savings performance contract. Under the terms of the contract, the ESCO will arrange private investment of about $18 million to finance the comprehensive energy efficiency upgrades in the family housing units. In return, the Army will pay the ESCO about 77% of the energy savings over 20 years. Under a separate term of the agreement, the Army will also pay the ESCO a specified fee per housing unit per month over the 20 years to maintain the measures installed that require maintenance (e.g., heating, cooling, lighting, etc.). This maintenance payment is also about 77% of the baseline maintenance cost.

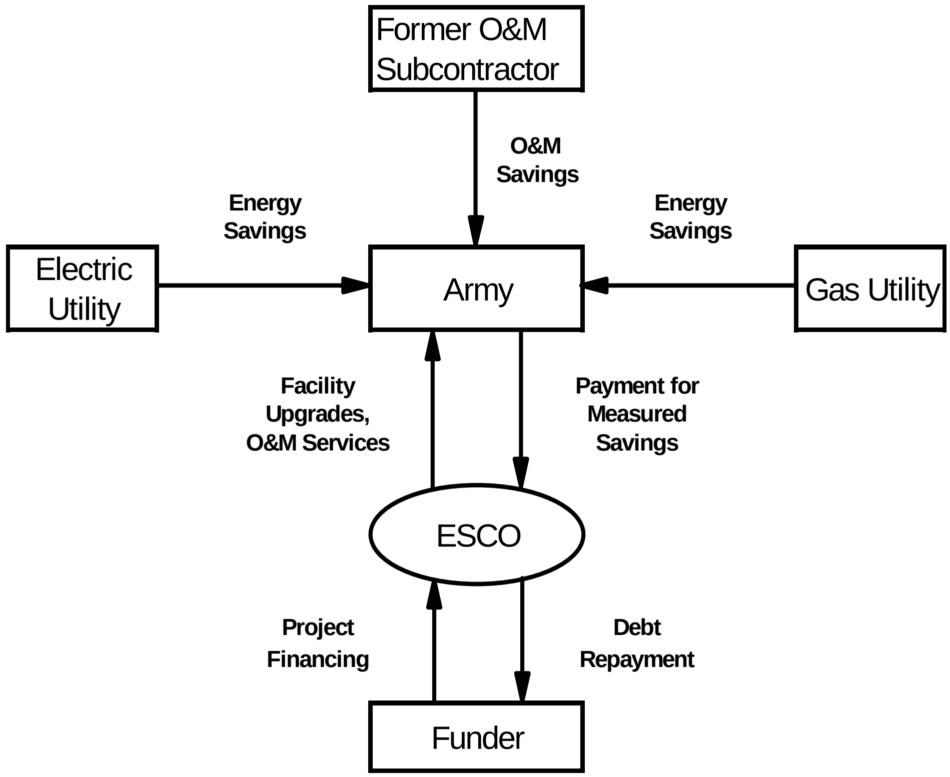

Fig. 1.1. Structure of the energy performance contract.

A variety of energy performance contract structures are in common use; the one used at Fort Polk is illustrated in Fig. 1.1. ESCO responsibilities include surveys, feasibility studies, design, financing, construction, and maintenance. The ESCO and Army agreed on estimated energy and maintenance savings, how savings would be verified, how actual savings would be shared, and who was responsible for what (e.g., the ESCO would be responsible for continued efficient performance of the measures installed, and the Army would be responsible for maintaining continued occupancy levels in the housing). The energy consumption of the housing area will be measured with community-wide metering recorded monthly, and energy savings will be estimated by subtracting recorded values from values estimated with a weather-normalized algorithm derived from the multiyear baseline data. The estimated energy savings and verification with measurements on pilot units were used by the ESCO to secure third-party financing. The "actual" savings, as determined by the agreed-upon M&V approach, determines the level of payment from the Army to the ESCO on a monthly basis (with the exception of the maintenance payment, which is stipulated in the contract). Further details of the ESPC have been presented by Aldridge (1995).

Performance contracts must be acceptable not only to the ESCO and the customer but also to the party that finances the project, since the contract's terms are critical to a financier's risk. Base closings and retail wheeling of electricity were among the issues raised by the funder during its due diligence review. They will likely be issues in any future projects of this sort. Several missions have been consolidated at Fort Polk since downsizing began, so the Army was able to commit to contract language to resolve the base closing issue. With regard to retail wheeling, the Army chose to reserve the right to shop for less expensive power for the base, but agreed to reopen negotiations with the ESCO if a significant change occurred. The electric utility in this case chose not to contribute energy efficiency incentives to the project. Had the utility been involved, retaining Fort Polk as a customer might have been a factor in the negotiation. It is significant to note that other federal customers have agreed in energy savings performance contracts (ESPCs) to assume the rate risk and to base ESCO payments on current rates stipulated in the contract.

Fort Polk offers a unique opportunity to obtain statistically valid data establishing the energy, demand, and O&M savings associated with GHPs in military housing. The authors believe the results of this project will also have relevance to public and private housing in general. The goals and objectives of the evaluation project at Fort Polk are summarized in the following section.

1.2 GOALS AND OBJECTIVES

The overall SERDP GHP Program objectives are (1) to develop awareness within DOD about GHPs, (2) to demonstrate GHP benefits to DOD, (3) to provide technical assistance and training, and (4) to provide GHP systems specification and procurement assistance.

Oak Ridge National Laboratory’s (ORNL’s) military family housing–related objectives in support of the overall SERDP GHP Program are (1) to determine statistically valid energy, demand, and O&M impacts of GHPs applied to military housing at Fort Polk; and (2) to improve the DOD capability to evaluate, design, install, operate, and maintain GHPs in military family housing.

Although its development is not part of this project, the authors believe that a framework is needed for conducting a national evaluation (or meta-analysis) across the various GHP applications and demonstrations. The Fort Polk project has been structured to contribute data to such a national evaluation, which would yield reliable engineering and implementation methods to evaluate, design, install, operate, and maintain GHPs in housing, military housing included.

With reliable GHP engineering and implementation methods, DOD would have the tools necessary to appropriately match implementation options (e.g., in-house design, construction, and O&M or outsourcing of functions separately or together) and funding sources (e.g., appropriations, private financing arranged by ESCOs, utility incentives, etc.) to the individual needs of military housing facilities.

2. DESCRIPTION OF THE BASE

Located in west-central Louisiana just outside of Leesville, Fort Polk is the site of the Joint Readiness Training Center (JRTC) that trains personnel from the Army, Air Force, Navy, and Marine Corps, as well as hosting country and civilian personnel, in airlift, close-air support, resupply, and battlefield combat missions. Fort Polk is also home to other units with varied military missions, such as the 2nd Armored Cavalry Regiment, the 108th Air Defense Artillery Brigade, and the 42nd Field Artillery Brigade. The 300-square-mile facility includes military offices, training centers, equipment and storage warehouses, a hospital, miscellaneous military facilities, and residential housing units.

While the base population varies with the requirements of national defense, about 9800 military personnel are currently assigned to Fort Polk, supported by more than 2000 civilian employees. Altogether some 23,000 military personnel and family members live in on-base housing. Of these, about 12,000 live in family housing.

2.1 EXISTING METERING

The electrical consumption for the entire Fort is measured by a single utility-maintained billing meter. However, 17 electric distribution feeds, each with submeters, serve the residential areas of the base. These submeters are read manually by Fort staff for internal utility cost allocation purposes (and now also for the performance contract M&V). The residential submeters were calibrated by nonmilitary personnel in 1992. Current transducers, which step down the primary electrical feeds, are used by the submeters.

Natural gas consumption at the Fort is measured by a single utility-maintained billing meter. Submeters isolating residential natural gas consumption are not available, but after the ESCO construction is completed, the housing will be all-electric, except for cooking in units that originally used gas for cooking.

2.2 HOUSING UNITS

There are 4003 individual residential units at the facility. The Fort Polk residential housing stock consists of both single-family and multi-family units built in nine construction phases between 1972 and 1988. Most housing is in multi-family units, primarily either duplex or four-plex buildings. Table 2.1 summarizes the housing stock by the year of construction, the number of units, and the heating and air-conditioning type.

North Fort and South Fort are two distinct housing development locations (Figs. 2.1 and 2.2). The South Fort housing area, on the south border of the facility, was constructed between 1972 and 1981. The most recently developed (1984 to 1988) North Fort housing area is located approximately 4 miles to the north.

Single-family homes typically were constructed in a ranch-style configuration. Multi-family buildings were constructed in various arrangements including single-story ranches, side-by-side townhouses, and flats with a two-story configuration. Multi-family buildings were constructed with two to six units per building. Typical exterior wall construction types are brick, stucco, aluminum and vinyl siding. Foundations are typically poured slab-on-grade construction. Various types of envelope insulation and windows were installed during the different construction phases.

The units constructed in 1972 and 1975 use natural gas for space heating, domestic hot water heating, and cooking. The remaining units operate with electric service only.

Table 2.1. Summary of Fort Polk housing stock

Year of construction	Number of units	Existing heating/air conditioning
	South Fort	
1972	260	Gas furnace/DX air conditioning
1975	500	Gas furnace/DX air conditioning
1976	1000	Air-to-air heat pump
1977	651	Air-to-air heat pump
1980	262	Air-to-air heat pump (solar domestic hot water)
1981	200	Air-to-air heat pump
	North Fort	
1984	200	Air-to-air heat pump (economizer)
1987	581	Air-to-air heat pumps (economizer)
1988	349	Air-to-air heat pumps
Total	**4003**	(1290 buildings)

2.3 DESCRIPTION OF THE RETROFIT

Under the terms of the performance contract, the ESCO is responsible for feasibility verification, design, financing, construction, and maintenance of the comprehensive energy efficiency upgrades to the existing 4003 housing units at Fort Polk. The housing improvements to be implemented are summarized in the next paragraph.

GHPs will replace existing air-source electric heat pumps and combinations of natural gas furnaces and central electric air conditioners. Because of the size of the heat pump order, the ESCO was able to negotiate specifications for the GHP units to improve efficiency and minimize installation labor. Electric and gas domestic hot water (DHW) heaters will be replaced with new electric units except in cases where existing electric units have significant service life remaining. In housing units where GHPs and water heaters are proximate to each other, GHP desuperheaters will transfer recovered heat to the water tanks. Lighting retrofits include a combination of delamping of existing fixtures, and replacement of other fixtures with compact fluorescent lights. Low-flow shower heads are to be installed in all units. Attic insulation is to be installed as needed. Water tank insulation wraps and other weatherization measures may be implemented as appropriate.

The GHPs are the major energy conservation measure. GHP system design has been completed using load calculation, equipment selection, and energy models for each of the existing 66 unique housing unit configurations. The final vertical ground heat exchanger sizes were selected from among four independent professional recommendations.

Approximately 75% of the GHPs will be equipped with DHW desuperheaters, which route recovered heat to the water tank by means of a small potable water recirculator. In cooling mode, this recovered heat would otherwise be rejected to the ground. In heating mode, the ground is the source of the recovered heat (i.e., the heating/water heating GHPs will operate for more hours than heating-only GHPs would, reducing tank resistance element operating hours).

Figure not available.

Fig. 2.1. South Fort housing area.

Figure not available.

Fig. 2.2. North Fort housing area.

3. EVALUATION DESIGN

The evaluation design was developed on an expedited basis to meet project requirements. At the time the project was initiated, the ESCO planned to begin construction in June 1994 and complete construction in 10 months. Under that scenario, any pre-retrofit summer peak data would have had to be obtained in the summer of 1994. The project funding actually was received in mid-August 1994. The evaluation was designed and monitored subsamples were mostly installed by the end of September 1994. Monitoring was fully installed by the end of October. In actuality, construction was delayed until March 1995 as the Army, ESCO, and the funding source negotiated over issues such as base closings and retail wheeling.

The evaluation design is required to meet several technical challenges and still be implementable within the likely multiyear funding resources available. The technical challenges are all related to meeting the objective of determining statistically valid energy, demand, and O&M impacts of GHPs applied to military housing at Fort Polk.

One technical challenge is to arrive at a design that can be implemented without interfering with the performance contract. This challenge led to a "pre-retrofit/post-retrofit" design, since all of the housing is being treated, leaving no suitable untreated control group. It also led to independent community-wide electric metering to obtain 15-minute-interval electric data and to avoid interfering with the measurement and verification associated with the performance contract (monthly manual readings of consumption). A second technical challenge is to separate GHP impacts from the comprehensive energy efficiency project impacts. This led to the requirement for some monitoring of individual GHP units at the end-use level. A third technical challenge is to determine statistically valid impacts. The ratio of GHP impacts to total impacts will vary at the housing unit level because of construction vintage, building size, variations in measures installed by the ESCO, and occupancy effects. Therefore, sampling at the housing unit level is required. A fourth technical challenge is to estimate GHP O&M impacts. This led to a census of the outdoor units (heat pumps or air conditioners) that were replaced by the GHPs to establish pre-retrofit replacement rates for those units.

The following sections describe the overall evaluation approach, the sampling frame and data description, the sampling design and sample selection, the survey data, and the O&M data.

3.1 APPROACH

For the electrical energy and demand impact evaluation, ORNL is using the common technique of a nested multi-tiered evaluation design. The evaluation maintains strong internal statistical validity by sampling buildings by construction vintage and size, monitoring all apartments in the sampled buildings, selecting an even smaller subsample of those buildings for expanded metering of apartments at the end-use level, and expanding sampled impacts to the housing population where they can be compared with community-level metering.

The field measurement approach includes three nested levels of site monitoring, with each level building on the preceding level of measurement. Level 1 addresses the housing community or project (i.e., the performance contract) as a whole; Level 2 isolates the information for individual apartments in sampled buildings; and Level 3 focuses specifically on the performance impacts of the GHPs via end-use measurements in a subset of the Level-2 apartments. All three levels are designed to record electrical energy and demand data before the retrofits occur (pre-retrofit) and after (post-retrofit). In addition, the base-wide utility-maintained billing meter information is available to the project.

Figure 3.1 illustrates the sampling frames and levels of measurement. The entire residential housing population consists of 1290 buildings (single- and multi-family structures) and 4003 individual housing units.

Level-1 metering includes 15-minute-interval data from submeters on each of the 17 electrical distribution feeds into the housing area. Some of these distribution feeds (or combinations of them) map exactly into single construction vintages, allowing comparisons between expanded sampled impacts and monitored population impacts at the vintage population level as well as at the community-wide population level, in some cases.

The Level-2 monitored subsample will consist of 24 buildings and 71 housing units selected from the population. Level-2 metering includes 15-minute-interval data for the apartment, as well as for the heating and cooling end use (the pre-retrofit outdoor unit, the post-retrofit GHP), at all 71 housing units.

The Level-3 monitored subsample will be a technical sample of 8 buildings and 29 housing units selected from the Level-2 sample to receive more extensive end-use metering in addition to the Level-2 metering.

ORNL's approach to the O&M impact evaluation is to develop an independent estimate of the O&M cost baseline (i.e., costs expected if the retrofits had not taken place). A census was taken of pre-retrofit outdoor units (heat pumps or air conditioners) to establish replacement rates for the outdoor units. The data from this census, plus Army and ESCO data, will be used in an analysis to estimate what O&M costs would be over the 20 years in the absence of the performance contract. The analysis approach will borrow heavily from previous work done by Alabama Power and the Electric Power Research Institute (EPRI) on air-source heat pumps (Lovvorn, 1985; Pientka, 1987).

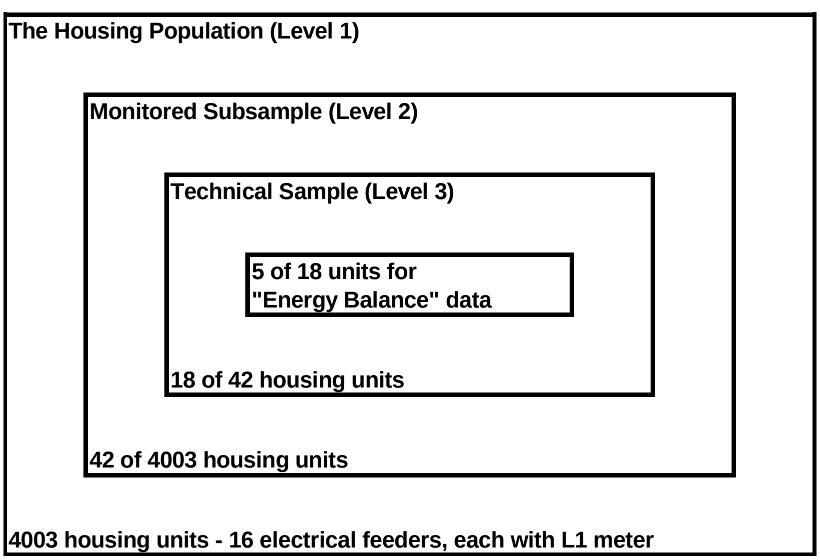

Fig. 3.1. Sampling frames and levels of measurement.

3.2 SAMPLING FRAME AND DATA DESCRIPTION

The family housing stock at Fort Polk consists of 1290 residential buildings with a total of 4003 housing units. Initial review of the data revealed that sufficient information was not available for building number 426. Consequently, it was eliminated from the study. Four buildings were found to have one dwelling unit facing a different street from all other units in that same building. The unique design of these four buildings raised the concern that they might have significantly different energy characteristics from the other buildings. Therefore, they were also excluded from the database.

The ESCO-conducted experimental pretests of GHPs piloted the comprehensive package of retrofits in several dwelling units so that demonstrated energy savings would be available to support efforts to arrange the financing. Because energy savings from the building will be treated as a whole, and savings from buildings with pilot units cannot be measured on the same basis, it was determined that these buildings should not be included in the sampling frame either. Thirteen buildings were eliminated from the database for this reason. Therefore, the final Fort Polk sampling frame consists of 1272 buildings.

A total of 880 buildings, approximately 69% of the entire Fort Polk sampling frame, were constructed in the 1970s. The year with the largest number of buildings constructed was 1976, when 404 structures were built. Figure 3.2 shows the number of housing units constructed in each contract year for the Fort Polk housing.

About 50% of the 1272 buildings in the sampling frame are duplexes (two-unit buildings). The next highest number, about 30%, are four-plexes (four-unit buildings). Figure 3.3 presents information about the number of buildings by size (measured by the number of dwelling units in the building).

3.3 SAMPLING DESIGN AND SAMPLE SELECTION

Because of the structural differences among buildings constructed in various years and potential variations in energy usage among buildings of different sizes, a stratified sampling approach was taken in this study. The year of construction (AGE) was grouped into four categories. In terms of building size, three variables were considered: (1) number of units in a building, (2) number of bedrooms in a building, and (3) square footage of living space within a building. Analysis of the data indicated strong correlations existed among these three variables; that is, the variables are providing essentially the same information. Therefore, the number of units per building (SIZE) was selected for simplicity. Buildings were classified into three size categories: one to two units, three to five units, and six or more units. The breakdown of buildings by age and size is given in Table 3.1.

Since no information was available on energy use, variations in building energy savings among all 12 age/size combinations were assumed to be the same. The overall sample size needed to draw valid results from the Fort Polk study was estimated as if it were selected for a single group (i.e., the entire population). Based on the coefficient of variation of energy savings in other military family housing units (Levins and Ternes, 1994) it was estimated that a sample size of 24 buildings would be necessary

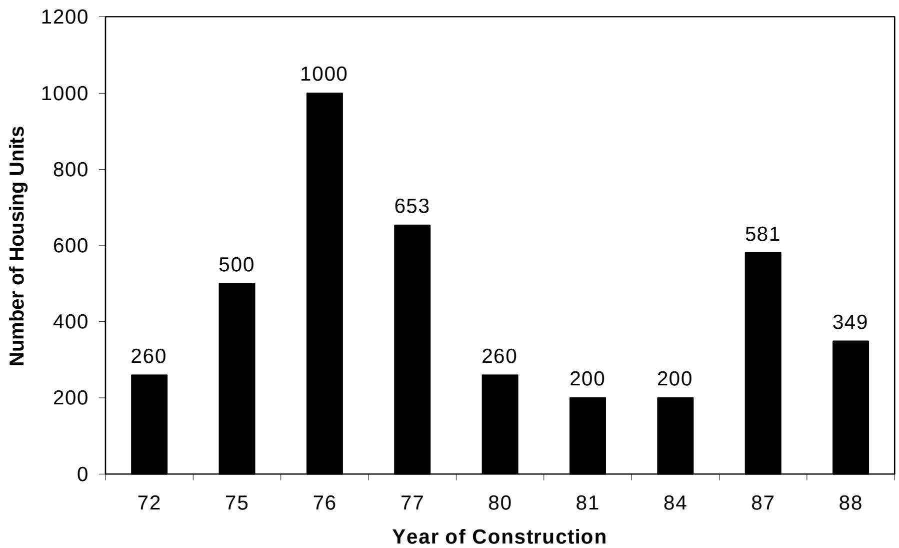

Fig. 3.2. Number of housing units by year of construction.

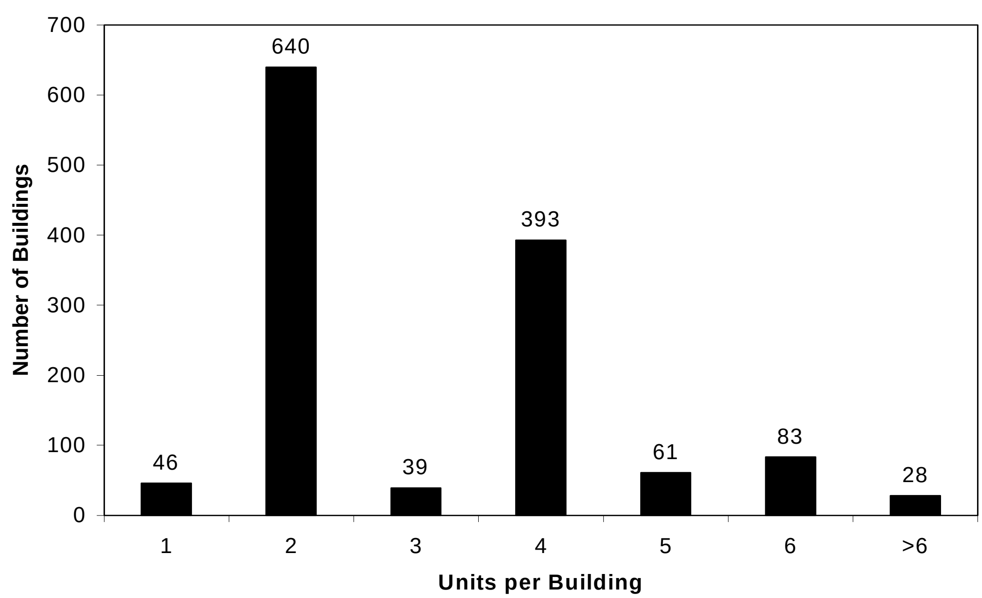

Fig. 3.3. Number of buildings by number of units per building.

to determine the mean energy use before and after the retrofits at the 95% confidence level. In future studies on other military bases a more refined method of sample size calculation can be developed by using the savings variation findings from the current project at Fort Polk.

Originally, a written occupancy survey was planned for a set of 200 buildings drawn at random from the 1292; however, because of strict privacy regulations protecting residents of military family housing, this survey was not carried out. The written survey sample of 200 buildings was the pool from which the Level-2 monitored subsample of 24 buildings was selected. The 24 buildings were randomly selected from among the 200, rather than allocating the 200 among the 12 AGE vs SIZE categories and then selecting randomly from each category. To accommodate the fact that some buildings may be very difficult to monitor during the site survey, ten sets of random survey samples were drawn independently from the population sampling frame. For each of these sets, a monitored subsample was also selected. These survey sample and monitored subsample pairs were provided to the field engineers. The field engineers started at the top of the pair list, and performed site surveys until they found a pair that did not pose unanticipated implementation difficulties.

For the Level-3 technical sample, eight out of the 24 Level-2 buildings were chosen for detailed end-use metering. These were selected to include a mix of buildings by vintage, size, and location.

The locations of the Level-2 and Level-3 monitored buildings are given in Table 3.2. Note that the level of monitoring is identified in the right-hand column.

Table 3.1. Breakdown of buildings by age and size

	Number of buildings with			
Construction year	**1 to 2 units**	**3 to 5 units**	**6 or more units**	**Total no. of buildings**
		Population		
1972 or 1975	171	74	17	262
1976 or 1977	425	167	38	630
1980 or 1981	4	81	10	95
After 1984	86	171	46	303
Total	**686**	**493**	**111**	**1290**
		Survey sample		
1972 or 1975	26	12	3	41
1976 or 1977	66	26	4	96
1980 or 1981	1	12	2	15
After 1984	14	26	8	48
Total	**107**	**76**	**17**	**200**

Table 3.2. Monitored subsample of 24 buildings

Bldg. No.	Street	Year	No. of Units	HP Model	Desuper-heater	Attic Area	Unit Size	No. of Bedrooms	Monitoring Level
4808	Reed Court	1977	2	VZ024	0	1,996	3,584	6	2
5007	Diamond Street	1972	2	VE030	1	2,970	2,970	8	2
5045	Stance LP	1972	2	VZ024	1	2,524	2,524	6	2
5104	Michael Drive	1975	4	VZ017	0	2,186	4,372	8	2
5185	Dietz Drive	1975	2	VZ024	1	3,162	3,160	8	3
5217	Monroe Drive	1975	2	VE030	1	3,162	3,160	8	2
5219	Monroe Drive	1975	6	VE030	1	5,712	10,158	24	3
5310	Monroe Drive	1975	2	VZ017	1	2,584	2,584	6	2
5379	Cline Court	1977	4	VZ017	0	3,456	6,692	12	3
5485	Bilger Court	1977	4	VZ017	0	2,348	4,696	8	2
5623	Mudry LP	1976	1	VZ024	1	1,794	1,794	4	2
5634	Bazydlo Street	1976	1	VZ024	1	1,794	1,794	4	2
5805	Warren Court	1981	4	VZ017	1	2,316	4,632	8	2
6204	Haag Street	1976	2	VZ024	1	1,804	3,456	8	3
6229	Haag Place	1976	4	VZ017	1	2,146	4,292	8	3
6306	Noldan Street	1976	2	VZ024	1	1,968	3,548	6	2
6342	Noldan Street	1976	2	VZ024	1	1,968	3,728	8	2
616	Jordan Court	1976	4	VZ017	1	2,146	4,292	8	2
6685	Tracey Place	1976	4	VZ017	1	2,146	4,292	8	2
6937	Garber Court	1980	5	VZ017	1	3,776	5,610	10	3
15314	Wise Street	1987	4	VZ017	1	3,362	5,700	10	3
15502	Turner Place	1987	4	VZ017	1	3,362	5,700	10	2
16112	Ryan Place	1988	2	VZ024	1	1,894	3,238	6	2
16410	Pinehurst	1988	2	VZ024	1	1,700	2,542	4	2

3.4 O&M DATA COLLECTION

The cost of O&M for heating, cooling, and water heating systems in housing is a major expense for the military. The military desires guidance on how to record and track pre-retrofit costs, predict post-retrofit costs, and structure performance contracts or other contracts to better manage costs.

Fort Polk has had a variety of O&M arrangements in the past, including in-house and subcontracted service. The availability of historical O&M data sources on actions and costs will be investigated.

The ESCO assumed responsibility for all energy-systems-related O&M in family housing about 12 months prior to the start of retrofit construction. Available records will be obtained on pre-retrofit O&M actions and costs. In cases where the ESCO alters the housing unit conversion sequence to avoid pre-retrofit O&M actions and costs, the avoided actions will be identified and costs estimated. ESCO willing, there will be collaboration with the ESCO to define post-retrofit O&M record keeping systems to be maintained by the ESCO for the duration of the 20-year performance contract.

Historical O&M practices and associated costs will be established by gathering and analyzing the available data, which may including the following:

- a census of pre-retrofit central air conditioner and air source heat pump outdoor units (performed as part of this project);
- the pre-retrofit O&M records of the ESCO (the ESCO pre-retrofit period is now significant because of construction delays);
- notes from interviews with base personnel and previous maintenance subcontractor personnel; and
- available base and subcontractor historical records on O&M costs and replacement costs for heating, cooling, and water heating equipment for housing.

The planned structure of the O&M analysis, including the basis for estimating GHP O&M impacts, is as follows:

- Document pre-retrofit O&M actions and costs in aggregate for the conventional heating, cooling, and water heating equipment in all base housing.
- Use historical data and industry data (i.e., Alabama Power and EPRI work on air-source heat pumps) to infer (or project) what O&M actions and costs would have been in the absence of the performance contract over the 20 years (i.e., establish a baseline).
- Use ESCO data to establish the near-term post-retrofit O&M actions and costs in aggregate for the GHP heating, cooling, and water heating equipment in all base housing.
- Use GHP industry data to infer (or project) GHP O&M actions and costs over the 20 years, or assume the contracted Army payments to the ESCO are a valid indication, and estimate the GHP O&M impact by subtraction from the baseline.

4. FIELD DATA COLLECTION AND ANALYSIS

The GHP project at Fort Polk provides a unique opportunity in that each of 4003 residential units is being retrofitted with a GHP. The diversity in housing stock, combined with the large housing population, allows the implementation of the statistically valid, nested, multi-tiered evaluation design described in Sect. 3.

This section describes more specifically the field data collection efforts undertaken to implement the community-wide Level-1 monitoring and the Level-2 and -3 monitored subsamples. The metering approach was designed to obtain three levels of information:

- Level 1: Project impact using community-wide electric energy and demand data, outdoor dry bulb temperature, and relative humidity.
- Level 2: Housing unit impact using total-residence and HVAC electric energy and demand data.
- Level 3: Separation of GHP from total impacts using additional electric end-use energy and demand data.

This section also describes more specifically the analysis approaches to be taken.

4.1 PROJECT ANALYSIS: LEVEL 1

The Level-1 metering and analysis focuses on the measurements of the impact of the project as a whole (i.e., the performance contract as applied to all housing). This includes not only the GHP impacts, but also all impacts derived from all energy conservation measures implemented via the performance contract.

The Level-1 metering installed for the evaluation parallels the existing Army submetering on each electrical distribution feed into the housing area. Fifteen-minute-interval electrical power measurements are taken at each of the 17 residential area submeters. These data are recorded on pole-mounted data loggers, and the data are remotely retrieved via telephone. For comparison, the Army manually logs cumulative readings from its submeters on a monthly basis. The Level-1 metering collects the data points identified in Table 4.1 at 15-minute intervals.

Table 4.1. Data points for typical Level 1, pre- and post-retrofit

Point name	Description	Units
TAO	Outdoor air dry-bulb temperature	°F
RHO	Outdoor air relative humidity	%
WT	Electric distribution feeder submeter energy (17 separate submeters)	kWh

Electrical Energy Savings Analysis

Preliminary analysis of the Level-1 pre-retrofit data indicates that daily average temperature is the most reliable predictor of daily electrical energy use for the electrical feeders which serve family housing. Data for a typical feeder serving all-electric housing is presented in Fig. 4.1. Electrical use evidently falls into three distinct regimes, depending on average daily temperature: a heating regime, in which energy use increases with decreasing ambient temperature; a cooling regime, in which energy use increases with increasing ambient temperature; and a mid-range, in which energy use is relatively constant and does not depend on ambient temperature. Ruch and Claridge (1992) have presented similar data for commercial buildings. Such data can be fit to a dual-changepoint model, which supposes a linear relationship between daily energy use and daily average temperature for the heating and cooling regimes, and constant energy use in the mid-range. The electrical energy use *E* for a particular day with average temperature *T* is given by:

$$E = \begin{cases} E_0 + m_1(T-T_1) & (T<T_1) \\ E_0 & (T_1 \le T \le T_2) \\ E_0 + m_2(T-T_2) & (T>T_2) \end{cases} \qquad \textbf{(4.1)}$$

where E_0 is a constant corresponding to the daily energy use in the midrange, m_1 and m_2 are the respective slopes of the heating and cooling regimes, and T_1 and T_2 are the respective heating and cooling changepoints. The line in Fig. 4.1 is a dual-changepoint fit to the data presented.

Figure 4.2 presents a similar plot of daily electrical use vs daily average temperature for a feeder serving housing with natural gas heating and water heating. Here only two regimes are evident: at low ambient temperatures daily energy use is relatively constant, but above a certain changepoint energy use begins to increase with increasing temperature. Data for the feeders serving housing heated by natural gas can be fit to a single-changepoint model, which assumes constant electrical energy use below the changepoint, and a linear relationship between daily electrical energy use and daily average temperature above the changepoint. For such feeders, the daily energy use *E* for a day with average temperature *T* is given by:

$$E = \begin{cases} E_0 & (T<T_1) \\ E_0 + m_1(T-T_1) & (T \ge T_1) \end{cases} \qquad \textbf{(4.2)}$$

where E_0 is a constant corresponding to the daily electrical energy use in the non-cooling regime, m_1 is the slope of energy use vs ambient temperature in the cooling regime, and T_1 is the cooling changepoint. The line in Fig. 4.2 is a single-changepoint fit to the data presented.

Pre-retrofit data on daily energy use vs daily average temperature for each feeder will be fit to either a single-changepoint or a dual-changepoint model, depending on whether the housing served is all-electric or gas/electric. After the retrofits all housing will be all-electric, so it is assumed that daily electrical use on each feeder will follow a dual-changepoint relationship. In order to correct for weather variations, annual pre- and post-retrofit energy consumption for each feeder will be normalized to a

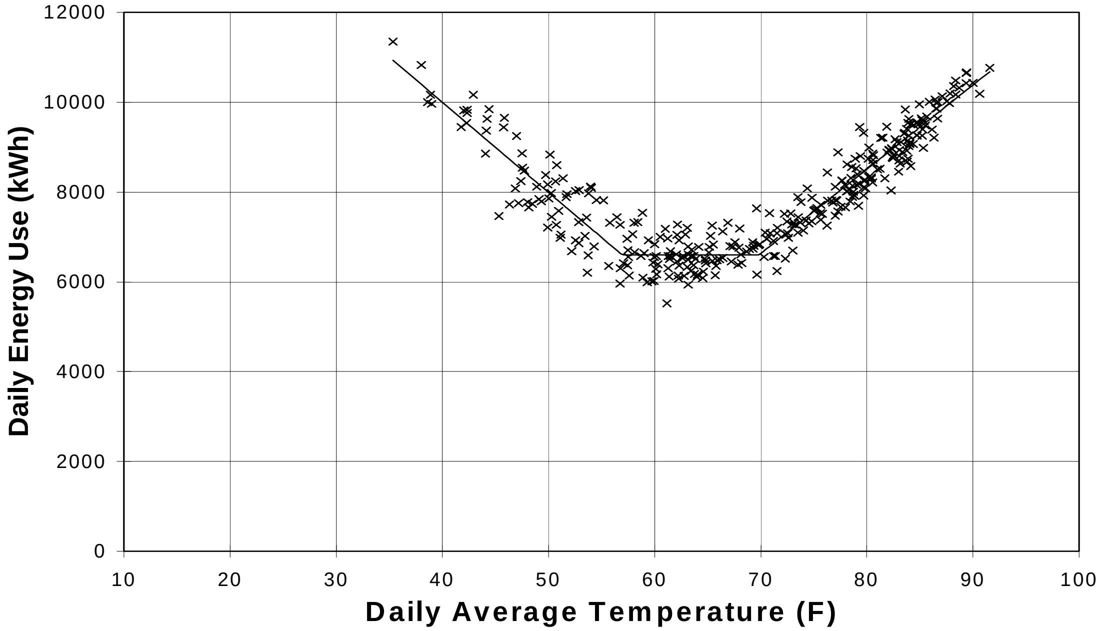

Fig. 4.1. Pre-retrofit daily electrical energy use for typical feeder serving all-electric housing.

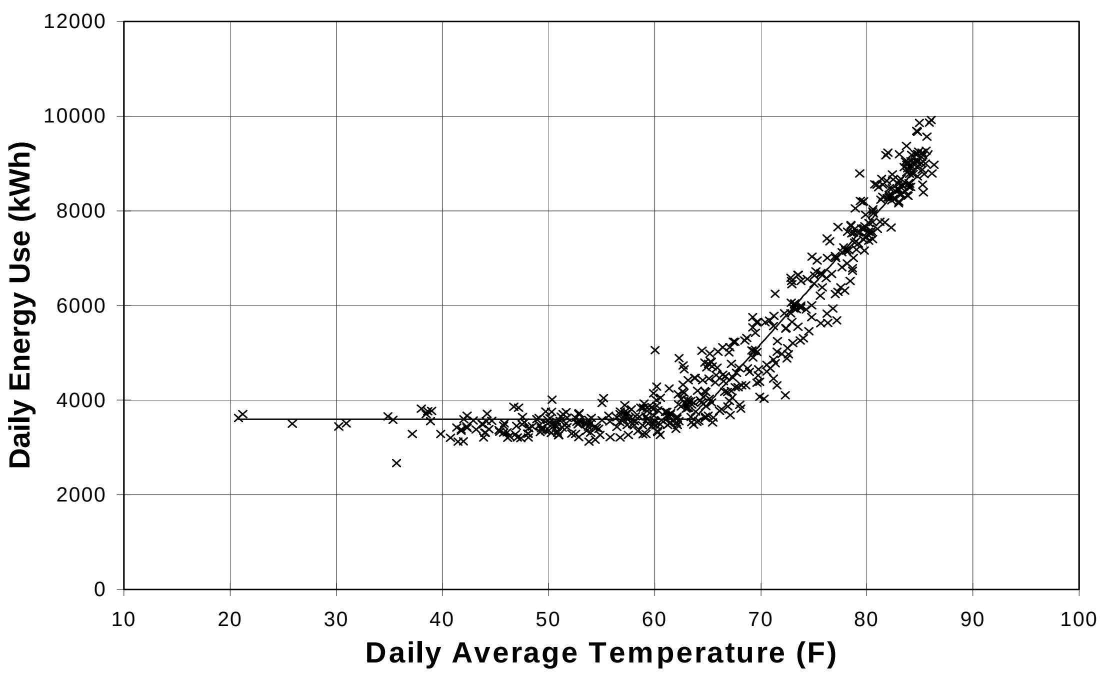

Fig. 4.2. Pre-retrofit daily electrical energy use for typical feeder serving gas/electric housing.

typical meteorological year. Thus for each feeder *I* the annual electrical energy savings ΔE_i will be estimated by:

$$\Delta E_i = \sum_{j=1}^{365} E_{i,pre}(T_j) - \sum_{j=1}^{365} E_{i,post}(T_j) \qquad \textbf{(4.3)}$$

where $E_{i,pre}(T_j)$ is the single- or dual-changepoint fit to the pre-retrofit data for feeder *I*, and $E_{i,post}(T_j)$ is a dual-changepoint fit to the post-retrofit data for feeder *I*. T_j is a set of 365 daily average temperatures corresponding to the typical meteorological year. The total estimated annual electrical energy savings from the project is then the sum of the energy savings from each feeder.

For the most part, the distribution of housing by feeder corresponds to construction vintage (i.e., all housing on feeder 11 was constructed in 1975, all housing on feeder 16 was constructed in 1987, etc.). The buildings in each construction vintage are identical except for compass orientation, and the living units are the same size except for small variations between upper and lower units. Thus Level-1 data will also be used to analyze the following:

- Pre- and post-retrofit energy consumption per unit vs construction vintage.
- Pre- and post-retrofit energy consumption per unit vs floor area.
- Energy savings per ton of cooling capacity installed.

Electrical Demand Savings Analysis

In general, electrical demand is a complex phenomenon which depends on numerous variables such as time of day and day of the week, outdoor temperature, average temperature during a number of past hours, average temperature during a number of past days, and others. Utilities commonly use five years or more of historical data for their demand models (Kim 1982). A rigorous analysis of electrical demand savings in this project would require the development of such models for both the pre- and post-retrofit for each feeder. As in the case of annual energy consumption, the models could then be normalized to a typical meteorological year to determine the savings.

For the purposes of this evaluation, a simpler approach will be used. It is assumed that daily average temperature is the dominant variable in determining peak electrical demand. The 15-minute-interval energy consumption will be used to determine daily electrical demand profiles for each feeder. Demand profiles from three pre-retrofit and three post-retrofit days with essentially identical temperatures will be selected and used to establish three-day-average pre- and post-retrofit profiles. Demand savings will be determined as the difference between the three-day-average profiles averaged over the 4:00 – 5:00 P.M. time period, which corresponds to the utility’s peak demand hour. As with the energy consumption data, pre- and post-retrofit electrical demand on each of the feeders will provide information on savings by construction vintage, living unit area, and installed cooling capacity.

Natural Gas Savings Analysis

The gas energy impacts are determined as follows. The only gas metering at Fort Polk the base-wide utility-maintained billing meter, and billing data will be available to the project. The South Fort housing built in 1972 and 1975 uses gas for space heating and water heating in the pre-retrofit condition and is all-electric in the post-retrofit condition. The Level-3 monitored subsample (see Sect. 4.3) will include two buildings and eight housing units with gas in the pre-retrofit condition (see Table 3.2). At these sites, furnace and water heater runtime are part of the 15-minute-interval data, and gas-burn rate constants are estimated from nameplate data. The Level-3 data will be used to estimate pre-retrofit gas consumption at the sampled sites normalized to weather indices, and that estimate will be expanded to the gas-connected population. The weather-driven pre-retrofit estimate will equal the project impact on gas consumption, since the post-retrofit condition for heating and cooling will be all-electric. Analysis of the pre-/post-retrofit gas billing data will provide another estimate for comparison, but this indicator may not be reliable because family housing may be a small part of the base-wide gas consumption, or the non-housing gas loads may have increased.

4.2 HOUSING UNIT ANALYSIS: LEVEL 2

Level-2 measurements and analysis focus on isolating energy and demand impacts on a sample of housing units. The approach provides pre-/post-retrofit electric energy and demand impacts in samples defined by construction vintage and building size.

The Level-2 sample comprises 24 buildings for a total of 71 individual housing units. In each housing unit the electrical energy for the whole residence and for the major end use, the air conditioner or heat pump outdoor unit, are metered at 15-minute intervals. These data are recorded on data loggers mounted to residential buildings and the data are remotely retrieved via telephone. The Level-2 metering collects the data points identified in Table 4.2 at 15-minute intervals.

Table 4.2. Data points for typical Level 2

Point name	Description	Units
	Pre-retrofit data	
TAO	Outdoor air dry-bulb temperature	°F
RHO	Outdoor air relative humidity	%
WT	Whole-residence electric energy	kWh
WAC	Air conditioner or heat pump outdoor unit energy	kWh
	Post-retrofit data	
TAO	Outdoor air dry-bulb temperature	°F
RHO	Outdoor air relative humidity	%
WT	Whole-residence electric energy	kWh
WAC	Geothermal heat pump unit energy	kWh

Electrical Energy Savings Analysis

As with the Level-1 data, analysis of the pre-retrofit Level-2 data indicates that daily average temperature is the most reliable predictor of daily energy use in each living unit. Figure 4.3 presents data from a typical all-electric residence. The line in that figure is a dual-changepoint fit to the data, an equation similar to Eq. 4.1.

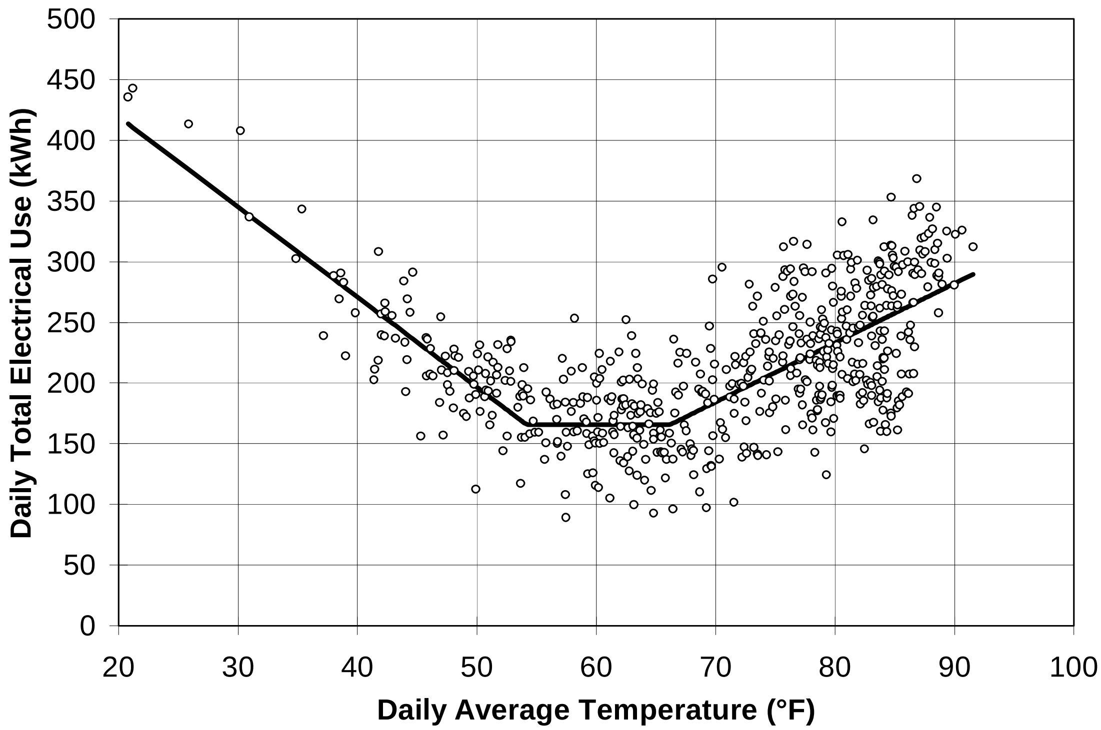

Fig. 4.3. Pre-retrofit daily electrical energy use for typical all-electric building.

Figure 4.4 presents pre-retrofit data from a typical gas/electric residence; the line represents a single-changepoint fit to the data, an equation similar to Eq. 4.2. In order to determine the electrical energy savings for each of the 71 Level-2 residences, pre-retrofit data on daily energy use vs daily average temperature will be fit to a single- or dual-changepoint model; post-retrofit data will be fit to a dual-changepoint model. The annual energy savings for each residence *i* will then be calculated by:

$$\Delta E_i = \sum_{j=1}^{365} E_{i,pre}(T_j) - \sum_{j=1}^{365} E_{i,post}(T_j) \qquad \textbf{(4.4)}$$

where $E_{i,pre}(T_j)$ is the single- or dual-changepoint fit to the pre-retrofit data for residence *i*, and $E_{i,post}(T_j)$ is a dual-changepoint fit to the post-retrofit data for residence *i*. T_j is a set of 365 daily average

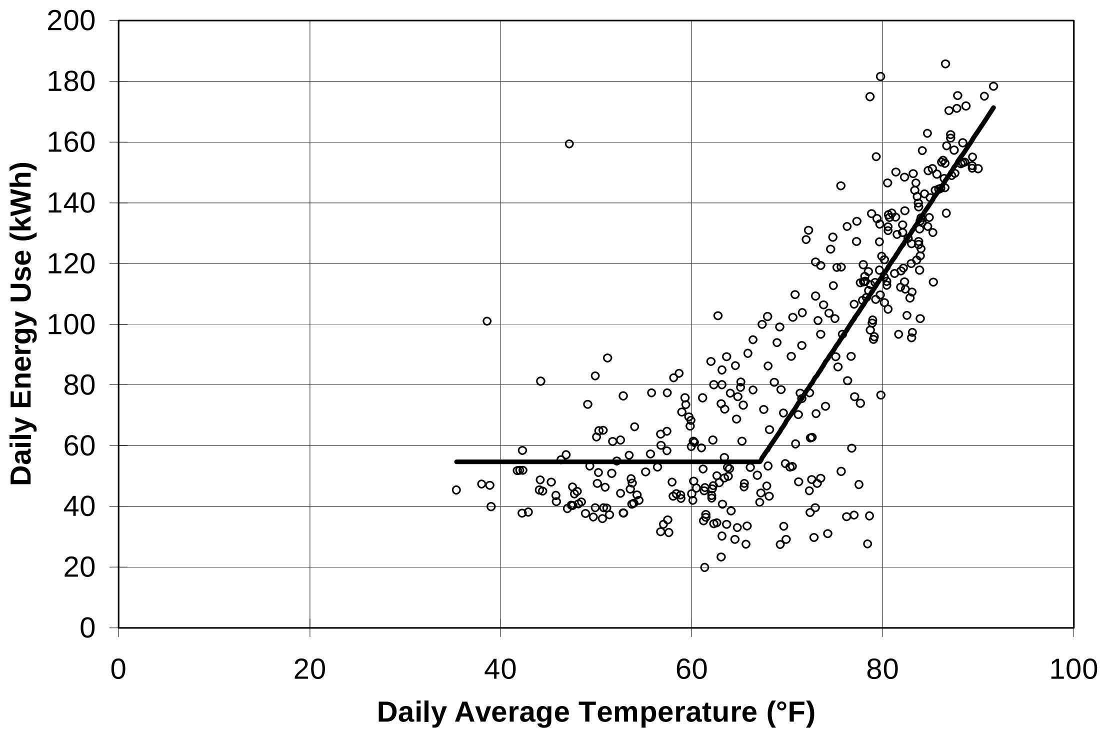

Fig. 4.4. Pre-retrofit daily electrical energy use for typical gas/electric building.

temperatures corresponding to the typical meteorological year. Similar pre- and post-retrofit fits will also be performed for the HVAC energy alone, to support determination of the proportion of the energy savings due to the GHPs.

Level-2 energy savings data will provide information on variations in energy savings by living unit area and construction vintage. An important test of statistical validity will be to scale up the pre- and post-retrofit Level-2 electrical energy use data to the Level-1 feeder data. This will be accomplished by forming weighted sums of the Level-2 electrical use data (the weighting will most likely be by floorspace). The HVAC curve-fits will be scaled up using the same weighting factors to determine the percentage of energy savings due to the GHP retrofits at the level of individual feeders and for the entire project.

Electrical Energy Demand Savings Analysis

Electrical demand savings for each of the 71 Level-2 housing units will be determined using a method similar to the Level-1 analysis. Average peak demand profiles will be obtained by averaging three peak days in the pre-retrofit and three peak days in the post-retrofit (all six days with similar temperatures). Average demand during the utility peak hour (assumed to be 4:00–5:00 P.M.) will be determined, and demand savings will be calculated by subtracting post-retrofit demand from the pre-retrofit demand. As with electrical energy use, demand from the Level-2 housing units will be scaled up to the feeder and project levels.

4.3 END-USE ANALYSIS: LEVEL 3

Level-3 metering provides more end-use breakout, but does so on a much smaller sample. The additional end-use measurements are taken on a technical subset of the Level-2 sample (8 of the 24 Level-2 buildings and 29 of the 71 housing units).

The Level-3 metering collects the data points identified in Table 4.3 at 15-minute intervals. Schematics identifying the pre-retrofit and post-retrofit monitored data points are presented in Figs. 4.5 and 4.6, respectively.

Table 4.3. Data points for typical Level 3

Point name	Description	Units
	Pre-retrofit data	
TAO	Outdoor air dry-bulb temperature	°F
RHO	Outdoor air relative humidity	%
WT	Whole-residence electric energy	kWh
WAC	Air conditioner or heat pump outdoor unit energy	kWh
RB	Indoor HVAC unit blower runtime	seconds
RD	Water heater runtime (electric element or gas burner)	seconds
RFE, or	Dwelling unit electric furnace runtime, or	seconds
RFG	Dwelling unit natural gas furnace runtime	seconds
	Post-retrofit data	
TAO	Outdoor air dry-bulb temperature	°F
RHO	Outdoor air relative humidity	%
WT	Whole-residence electric energy	kWh
WAC	Air conditioner or heat pump outdoor unit energy	kWh
RB	Indoor HVAC unit blower runtime	seconds
RD	Water heater runtime (electric element)	seconds
TL	GHP entering temperature from ground heat exchanger (when flow is on)	°F

Level-3 energy analysis will provide a basis for separating GHP impacts from total impacts with the following information:

- whole-residence pre-/post-retrofit electrical energy and demand impacts,
- water heating pre-/post-retrofit electrical energy and demand impacts,
- whole-residence and end-use residential load profiles,
- separation of GHP impacts from total impacts,
- impacts in samples defined by construction vintage and building size,
- expansion of sampled impacts for comparison with community-wide or feeder-by-feeder impacts,
- whole-residence and end-use load dependence upon outdoor dry-bulb temperature and relative humidity, and
- gas pre-retrofit heating and water heating consumption in 1972 and 1975 construction.

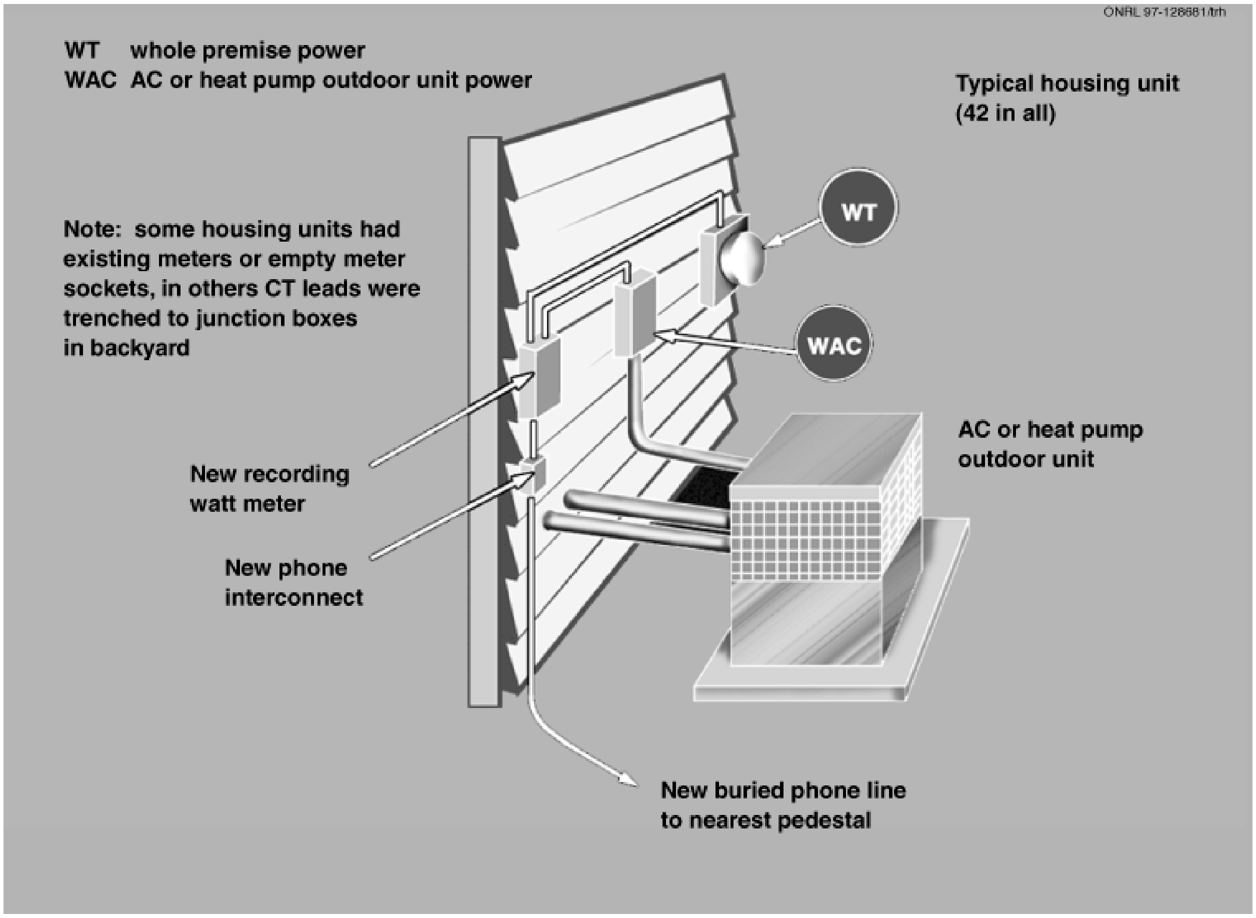

Fig. 4.5. Pre-retrofit monitored points.

The energy efficiency upgrades installed by the ESCO vary by construction vintage. All units will receive GHPs for heating and cooling. About 75% of the units will receive GHP contributions to water heating via potable water recirculation through desuperheaters. All units will receive compact fluorescent lights in some lighting fixtures, and a reduction in the number of incandescent bulbs in other fixtures. Most units will receive new electric water heaters, tank wraps, pipe wraps, and low-flow shower heads. Some of the units, especially the older ones, may receive various weatherization measures (e.g., caulking, weatherstripping, duct repairs). The ESCO is using detailed surveys and a work order system to control the measures that are installed in each unit. This information will be available to the project.

The objective of the Level-3 analysis will be to build detailed energy use models for each of the 29 monitored apartments. From the Level-2 analysis (section 4.2), pre- and post-retrofit models will exist for both daily total energy use and daily energy use for the HVAC system vs daily average temperature for each of Level-3 apartments. Level-3 data on energy use for water heating will be used to develop pre- and post-retrofit models of daily energy use for water heating by apartment floorspace; if significant

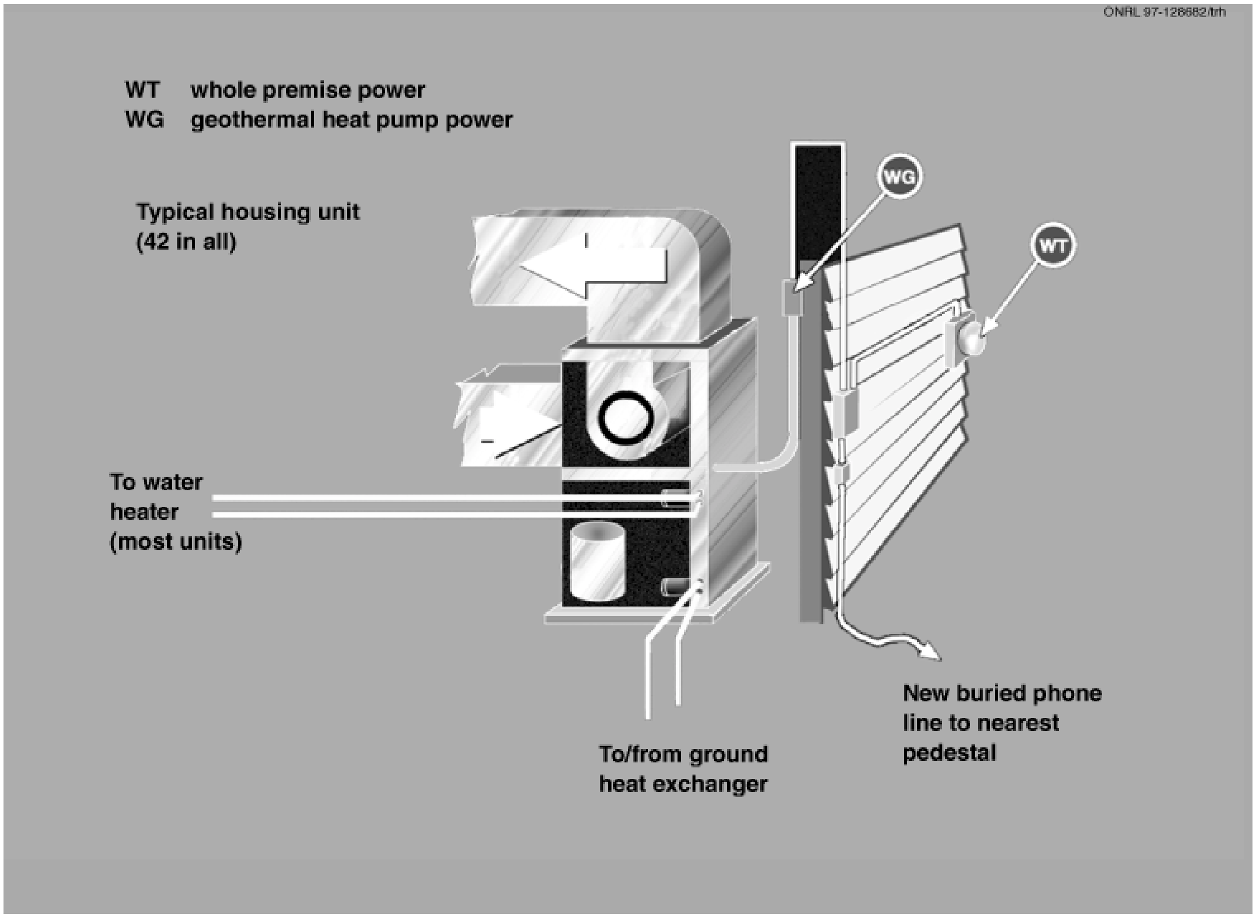

Fig. 4.6. Post-retrofit monitored points.

seasonal variations exist, this will be incorporated into the models as well. Post-retrofit models will be developed for apartments with and without desuperheaters.

Pre- and post-retrofit data will be available on total energy use, energy use by the HVAC system, and energy use by the water heater. Subtracting HVAC and water heating energy use from the total gives all other electrical use in the apartment, including lights, televisions, radios, etc. Since this includes the effect of the lighting retrofits, the daily pre- and post-retrofit "appliance load" will also be analyzed to determine how it varies by apartment floorspace; seasonal variations may be included in the model as well if they are found to be significant.

For each of the Level-3 apartments which was all-electric in the pre-retrofit, models of the following form will exist:

$$E_{tot} = E_{HVAC}(T) + E_{DHW}(A) + E_{APP}(A) \qquad \textbf{(4.5)}$$

where E_{HVAC} is a single- or dual-changepoint model of pre-retrofit daily energy use in the HVAC system vs daily average temperature; E'_{HVAC} is a dual-changepoint model of post-retrofit daily energy use in the HVAC system vs daily average temperature; E_{DHW} and E'_{DHW} are linear functions of apartment floorspace

$$E^{/}_{tot} = E^{/}_{HVAC}(T) + E^{/}_{DHW}(A) + E^{/}_{APP}(A) \qquad \textbf{(4.6)}$$

area A (and possibly including other terms to capture seasonal variations) for pre- and post-retrofit daily energy use for water heating; and E_{APP} and E'_{APP} are linear functions of apartment floorspace area A (and possibly including other terms to capture seasonal variations) for pre- and post-retrofit daily energy use for the other electric appliances, including lighting. When weighted according to the distribution of apartment floorspace in the housing population, these models will allow determination of the proportion of total savings which are due to each retrofit measure.

4.4 ANALYSIS WITH ENGINEERING MODELS

DOD needs more confidence in methods to estimate the financial value created when GHPs are placed into service, and more confidence in GHP design methods. To fulfill this need, this project will use as a starting point, the design and energy estimating methods and assumptions of the ESCO and its subcontractors. In addition to establishing the actual GHP and total project impacts at Fort Polk, as explained previously, this project will answer the question "if you had it to do over again, how would you perform the GHP design and energy/demand estimating for this project?"

The ESCO designed the project using ACCA Manual J load calculation, ACCA Manual S equipment selection, and bin analysis energy models for each of the 66 unique housing unit configurations that exist at Fort Polk. These estimates were then expanded to the population based on the number of units of each type. The final vertical ground heat exchanger sizes were selected from among four independent commercially available heat exchanger sizing programs. As part of this project these methods will be brought in-house, studied, and compared with other available methods as well as with the Level-1, -2, and -3 monitored data. These comparative analyses will result in the selection of recommended sets of methods and recommended assumptions for these methods.

The general approach will be as follows. In all apartments of one of the Level-3 buildings, additional instrumentation will be installed to monitor the operation of the ground source heat pump: ground loop inlet and outlet water temperatures, reversing valve status (heating or cooling position), desuperheater status (on/off), and indoor temperature and humidity will be monitored at 15-minute intervals. A detailed dynamic simulation of each apartment, its installed GHP, and controls, will be developed and calibrated to the field-monitored data. These dynamic models will then be used to generate the space conditioning load data required for the four ground loop sizing software packages used by the ESCO.

A dynamic model of the ground heat exchanger will also be incorporated into the model for each apartment using the duct ground heat storage model (Hellstrom et al., 1996) developed at the University of Lund, Sweden. The model was chosen because it is well documented, validated, and considers multi-bore interactions and long-term (multiyear) effects. Since the Lund model requires as input the heat transfer properties of the soil, calibrating the model to field-collected data on inlet and outlet water temperatures will allow the soil properties at the site to be determined. Since the ESCO based its ground loop designs on soil properties measured using conventional methods, this “reverse engineering” of soil properties will provide a useful comparison.

The dynamic energy use model for each apartment and its associated GHP with ground loop and controls, will provide a calibrated benchmark for comparison with other commercially available ground loop sizing software. For example, if it is found that the ground loops are oversized, the dynamic models can be used to determine the correct size which would give a specified maximum entering water temperature. This will provide information on the accuracy and usefulness of more practical sizing methods.

5. CONCLUSIONS

A statistically valid, nested multi-tiered evaluation strategy has been developed to determine the energy savings due to an energy savings performance contract at Fort Polk, Louisiana. The evaluation will determine the overall energy savings from the project, and the proportion of these savings due to each conservation retrofit, the most important of which is the installation of a geothermal heat pump in each residence. Based on maintenance records collected before the retrofits, the evaluation will also estimate the Army's pre-retrofit maintenance cost, and determine the maintenance cost savings associated with the ESPC. Based on detailed data collected at one building, the evaluation will also develop a detailed dynamic model of the building/GHP/ground loop/controls system which will be used as a benchmark for comparison with commercially available ground loop sizing software.

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