ACT^2 Project: Maximizing Residential New Construction Energy Efficiency

Lance E. Elberling, Pacific Gas and Electric Company
Richard C. Bourne, Davis Energy Group, Inc.

A large U.S. utility designed, built and is monitoring two single family homes to test the hypothesis that substantial energy savings (perhaps as high as 75% over current practice) can be achieved in residential buildings, at economically acceptable costs, through the use of integrated energy efficient end-use technologies and systems.

The goal of the "Advanced Customer Technology Test for Maximum Energy Efficiency" (ACT^2 Project) is to provide scientific field test information, for use by the utility and its customers, on the maximum energy savings possible, at or below projected competitive supply costs, by using modern high-efficiency end-use technologies in integrated packages acceptable to the customer.

ACT^2's residential efforts started with the designing and constructing of two new single family homes located in California's Central Valley. Each design maximizes energy efficiency by installing integrated packages of energy efficiency measures (EEMs) that improve the efficiency of appliance and lighting loads and more importantly reduce or eliminate the need for mechanical cooling in a climate with a 105°F design temperature. The two ACT* residential designs have produced projected savings of 62% and 64% in total energy consumption at mature market costs competitive with new supply. Construction of the two homes was completed in December 1993 and April 1994 and ACT^2 is now monitoring actual energy use and EEM performance.

Introduction

The advent of highly efficient end-use technologies has led energy efficiency advocates to hypothesize that large savings are possible at costs less than new energy supply. These advocates estimate that by using these technologies in integrated packages in residences the savings might be as great as 75%. The hypothesis, however, has not been thoroughly tested.

The Advanced Customer Technology Test (ACT^2) for Maximum Energy Efficiency Project is a major research and development effort that will scientifically test this hypothesis for residential use by controlled demonstrations in conventional style new construction homes in California. The energy saving packages of technologies can be conceived of as "negawatt power plants," (PG&E 1990) which suggests that utilities could invest in customer energy efficiency as an alternative to building new power plants and delivery systems to meet future load growth. This concept applies to residential natural gas end-use technologies as well.

In August 1990, the utility initiated this multi-year research and development project with initial funding of $10 million through 1992 (PG&E 1990). Another $9 million has been authorized for continuing the project into 1996. This funding established two new construction single-family homes, two existing single-family homes, three commercial sites and one agricultural site.

The project consists of demand-side demonstrations to measure actual economic and technical performance of the integrated packages, and to determine adverse or beneficial effects on the user. In addition, impacts on the site environmental quality are being monitored. Major tasks for each new construction demonstration include:

- Site investigating, prioritizing and selecting;
- Contracting with home builders;
- Baseline modeling;

- Design, purchase, installing and commissioning of integrated energy efficiency package;
- Operation by the utility and then the owner
- Post-monitoring, analysis, and reporting

To determine economic competitiveness, the investment in energy efficiency measures in the homes have been treated as if they were a power plant, i.e., utility discount rates and life-cycle costing were used. By this treatment, the decision to make an investment in demand-side measures has been made on the same basis as for a supply-side investment, and the unit costs of both options has then been compared fairly. Since many of the candidate energy efficiency measures are just emerging, estimated mature market costs, rather than current market costs have been used to more realistically reflect each EEM's competitiveness.

Methodology

Site Selection

To select the new construction sites in California's Central Valley, California's Title 24—Building Energy Efficiency Standards (CEC 1988) residential compliance calculation submittals were reviewed for 750-1000 new homes being built in the Central Valley during the last six months of 1991. The review determined that the average size of new homes was 1691 ft^2 (157 m^2). Further it was determined that the majority of homes built in the central valley are wood frame construction with slab-on-grade foundations. Consequently, any new construction home using wood frame construction and a slab-on-grade foundation in the 1500 to 2000 ft^2 (140-190 m^2) size range was considered for participation.

The new construction sites were chosen from a field of 8 nominees. The nominees included one custom home, 4 models submitted by high volume tract builders and 3 models submitted by low volume tract or semi-custom builders from throughout the central valley. The minimum requirement for final selection was the builder's willingness to remove a candidate site from his standard construction schedule, in order to allow for the ACT^2 design process which would add 4-5 months to the normal design period. The second consideration was the willingness of the builder/occupant to consider changes to the original design including building exterior, orientation, shell construction, interior layout, HVAC system and appliances. The final consideration was the level of the quality of the homes the builder constructed.

The first new construction site is a single family residence located in Davis, California, a community approximately 15 miles West of Sacramento. The nominated site was a 1656 ft^2 (155 m^2), single-story ranch-style home. The house was designed to have a 4 inch thick concrete slab-on-grade foundation, wood or stucco exterior over 2 by 4 wood framing with 16 inch stud spacing, R 13 fiberglass batt insulation, dual pane windows with vinyl frames and a concrete tile roof. The interior space was intended to have 35% vaulted ceiling using a non-truss system with the remainder of the house using 8 foot ceilings. A conventional ducted forced air heating and compressor based cooling system would have been installed in the house by the builder.

The second new construction site was chosen from the remaining 7 nominees. It is located in Rocklin, California a community approximately 30 miles Northwest of Sacramento. This site was chosen because the Summer climate is more severe than at the Davis site. In Rocklin the day time temperatures average 2-3 degrees higher and the night time temperatures do not fall as they do in Davis. This situation increases the cooling loads on the building.

The basecase house is a 1683 square foot single story model with a lot oriented on a Northeast/Southwest axis. The house has a 4 inch thick concrete slab-on-grade foundation, wood siding over 2 by 4 wood framing with 16 inch stud spacing, R13 fiberglass batt insulation, dual pane windows with aluminum frames and a concrete tile roof. The interior space is 50% vaulted ceilings with the remainder of the space using 9 and 10 foot ceilings. The builder normally installs conventional forced air heating and compressor based cooling systems in the other houses in the tract.

Model Development

A DOE2.lE (LBL 1991) model of each site was created for each site using construction drawings of the basecase houses, California's Title—24 Building Efficiency Standards assumptions, weather tapes adjusted for local weather conditions and utility billing history from similar houses which had been built by the developer within the previous 18 months. The model was used to determine how energy would be used in the houses if they had been built. This information allowed the designers to focus their attention on the areas of highest usage first.

ACT^2 Design Approach

Traditional residential building practice has been based on repeating what worked in the past to ensure least cost construction, rather than designing each project to take advantage of site conditions. Subcontracts for all or most of the house's systems are awarded to the low bidder and subcontractors tend not to collaborate on design or installation. This process results in systems that are oversized, to provide a margin for safety, and equipment substitutions that result in lower efficiency to keep the cost down. The ACT² design process emphasizes designing all building systems to optimize their integrated performance. Engineers work closely with the architects, subcontractors and builders as a team to integrate all aspects of the home and capture every opportunity to maximize efficiency, reduce costs and ensure proper sizing and performance.

The primary objective of the design team at both the Davis and Stanford Ranch sites was to maximize the energy efficiency, within economic constraints, by providing the greatest possible external and internal thermal loads reduction, use the load reduction to reduce the size of the HVAC equipment, and install the highest efficiency equipment available to minimize the remaining energy consumption. This goal was achieved by paying close attention to all aspects of the design process to produce an integrated design, that captured savings generated by synergistic system interaction.

However customer acceptance of the technologies was an equally important aspect of the design process. Since the ultimate customer/home owner was not available to evaluate acceptability, the builders were interviewed throughout the process regarding EEM acceptability. During the preliminary and final design phases, the builders were asked to review the technologies being considered as well as the design. Design features and/or technologies that the builder thought a customer would be unwilling to accept were removed from the design and replaced with the next most efficient technology or design feature.

Schematic Design

The first design task was to control solar gain. The cost effectiveness of a south-facing site and building orientation to take full advantage of winter solar gain was evaluated. The envelope shape, perimeter length, amount and location of the glazing was analyzed. Several alternative perimeter configurations, glazing areas and glazing placement options were considered for both sites.

Preliminary Design

The Preliminary Design phase of the project for both sites consisted of three steps:

1) EEM Screening
2) Multiple Package Development
3) Design Reports

EEM Screening. A Master Technology list was reviewed for each site to identify potential EEMs. Information on specific performance, potential for providing interactive savings, and mature market pricing was gathered and analyzed by the design team. Based on this information the EEMs were ranked by the benefit cost ratio.

EEM Packaging. It was decided that trying to develop a single design ran the risk of not achieving the most efficient design. Therefore, it was decided that the design team would develop and compare multiple packages of EEMs and then choose the one best suited to the site, the customer and the available technologies.

The ACT² Design and Build Team used a sequential analysis technique (Bourne 1994) to build each of the packages from the ranked list of EEMs. EEMs were added to the supply curve (Meier 1982) up to the point where the cost of the EEM is equal to 100% of the cost of new supply, measured in cents per kWh (see Figure 1). Whenever the inclusion of an EEM allowed additional savings in a previously ranked EEM, those savings were attributed to the EEM higher on the curve and thereby reduced the Cost of Conserved Energy (CCE)[1] for that EEM. For example, if high performance windows, which in California's relatively mild climate have a high CCE and are therefore high on the supply curve, allowed the down sizing of the air-conditioning unit, the dollar savings would be credited to the windows thereby moving the windows further down the supply curve. To allow the inclusion of interesting technologies which may be above the cost of new supply, and to allow for uncertainties in the mature market cost estimates, the designer were allowed to list EEMs up to 150% of the cost of new supply. The multiple packages were then reviewed by the project staff and the steering committee for design validity and to determine which EEM's with costs greater than the cost of new supply will be included in the final design.

Preliminary Design Report. The performance and cost projections for the package of EEMs selected from the multiple packages were further developed and the sequential analysis was updated. The Preliminary Design Report presented the refined package of EEMs selected, including details of the design process, architectural drawings, system schematics drawings, performance calculations, product literature and the DOE2.1 E model used for design. The report was presented to the builder for review and comment before submission to the ACT² Steering Committee for review and comment.

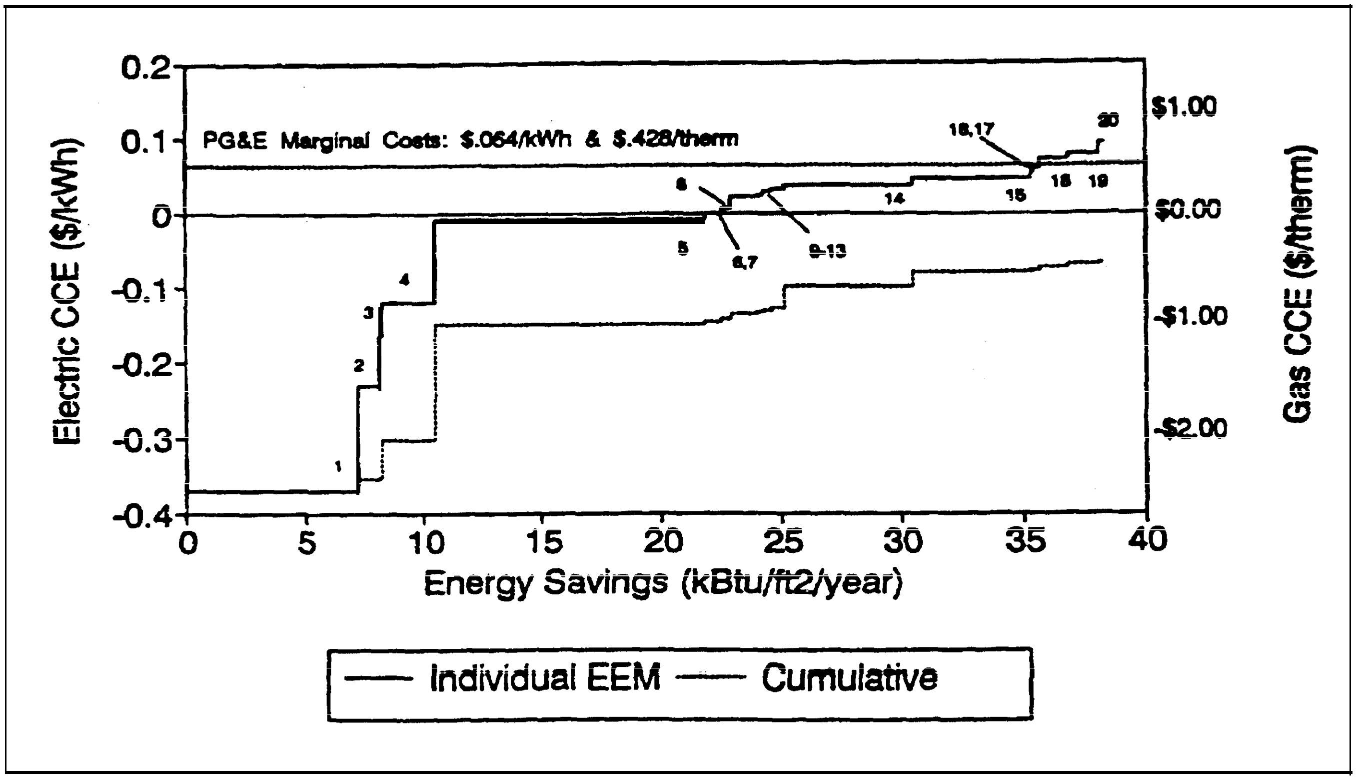

Figure 1. Combined CCE Supply Curve

Final Design

The final design phase was used to incorporate Preliminary Design review comments by the ACT[2] Steering Committee and to refine the cost and performance projections for each EEM within the selected package. The sequential analysis was updated and new supply curves were generated. The Final Design was again reviewed and approved by both the builders and the ACT[2] Steering Committee. Additionally, as part of the final design phase construction drawings were finalized, building permits were applied for and a Commissioning Plan was written.

Results

Schematic Design

While neither house could be reoriented on the lot, a unique form was selected for each house which minimized perimeter length and glazing area. The reduced perimeter resulted in decreased exterior wall surface area thereby reducing overall thermal gains and losses and the reduced glazing area decreased the heat loss in the winter. The Davis house provided the greatest opportunity for reducing perimeter length. As is shown in Figure 2 below the irregular shape of the basecase house was changed to a rectangle, with an elongated southern elevation, this change resulted in a perimeter length reduction of 33 feet.

Glazing was concentrated on the southern elevations to maximize insulation and allow architectural overhangs to shade the glazing in the summer. Total glazing area was reduced to 11% and 14% of floor area at Davis and Stanford Ranch sites respectively and East and West glazing was minimized or eliminated all together. The design models at both the Davis and Stanford Ranch sites showed that these strategies reduced space conditioning loads by 23% and 18% respectively and also reduced the cost of building the houses.

Preliminary Design

For both sites the Schematic Design established siting and form as the first EEM. For the Davis site, the sequential analysis established envelope improvements as the next three EEM's followed by a number of space and non-space conditioning EEMs. The Stanford Ranch sequential analysis also ranked shell improvements second, followed by a various non-space and space conditioning EEMs.

EEM Screening. During the screening process the Design Build Team reviewed 84 potential technologies for inclusion in the Davis and Stanford Ranch site designs. Of the technologies considered more than 60 passed the screening and were ranked by CCE.

Field surveys of other houses both builders had under construction indicated that the average wood content in the

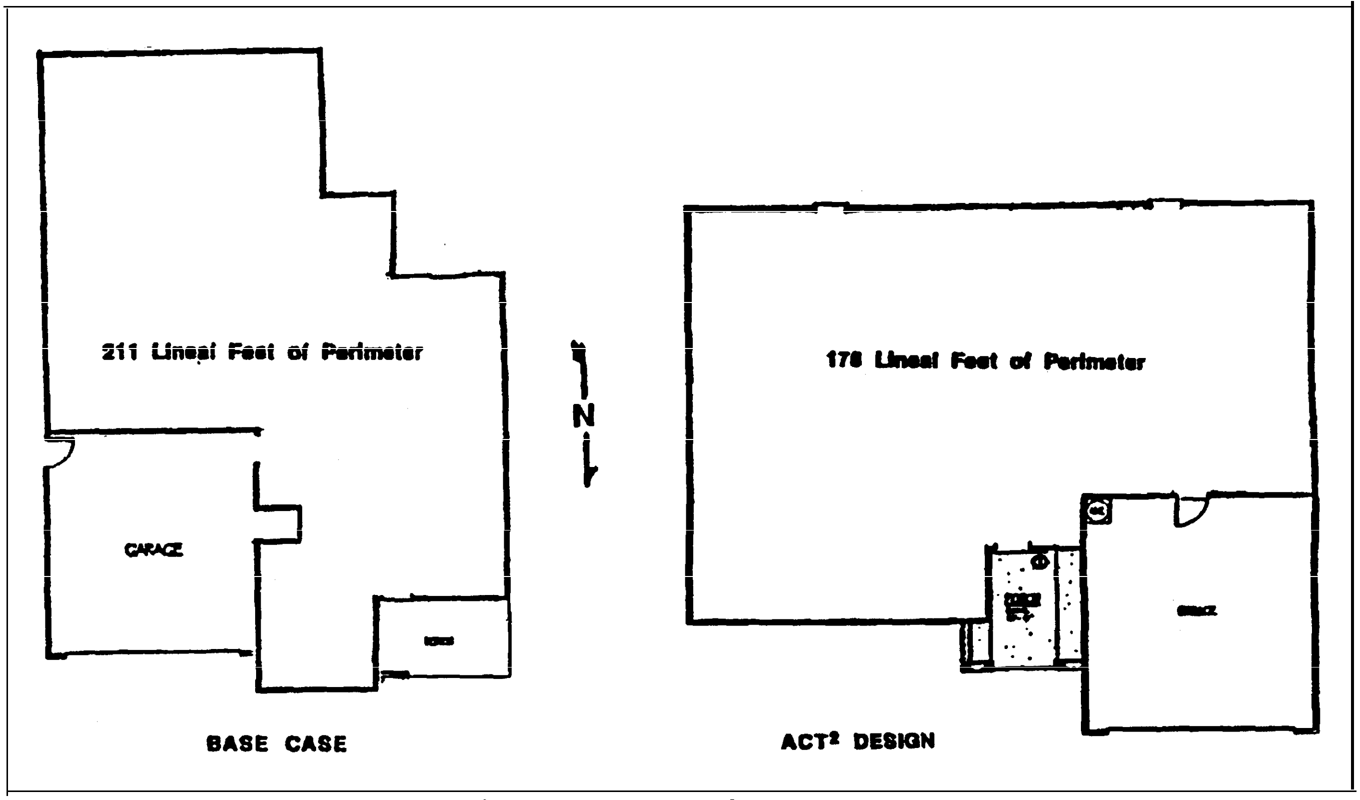

Figure 2. Davis Site Schematic Design

opaque wall areas (not including window and door areas) was 35% and 30% respectively. Because of this the first EEM, after siting and form, became reducing the wood content in the walls and increasing thermal resistance. This resulted in the development of the Engineered Wall Framing (EWF) system.

The EWF system (see Figure 3) design reduced the wood content to approximately 9% and increased thermal resistance by using the following elements:

- 1-1/4 inch thick studs placed on 24 inch centers,
- a 16 inch by 1-1/4 inch wide continuous headers attached to the inside edge of the stud allowing insulation behind the headers,
- single 1-1/4 by 3-1/2 inch top plate
- 3-1 /2 inches of isocyanurate rigid foam insulation between studs,
- 1-1/4 inch foam spacers attached to the inside edge of the studs,
- 1-1/4 inch air space between insulation and dry wall

The EWF system, which was used for both Davis and Stanford Ranch sites, was combined with R-38 attic insulation, a high performance tuned glazing system, insulated doors and attic radiant barrier, this resulted in the envelope performance projections listed in Table 1.

EEM Packaging. The siting, form and building envelope EEMs had reduced the HVAC loads to the level where a single high efficiency hot water heater could meet both space and domestic water heating (DHW) demand. The design team was then able to sort all EEMs into packages which attempted to reach specific space conditioning system design strategies. As the HVAC system was being developed the lighting, refrigeration, appliance and other EEM's were selected through the sequential analysis process. At the Davis site, four HVAC system strategies were identified and evaluated:

1) forced air heating and compressor based cooling
2) forced air heating and ducted evaporative cooling
3) radiant floor heating and Indirect/direct evaporative cooling
4) radiant floor heating and ventilative cooling

As the Davis site packages were developed, it became obvious that package no. 2, the forced air heating and ducted evaporative cooling strategy, was not cost effective and it was eliminated. The development of the three

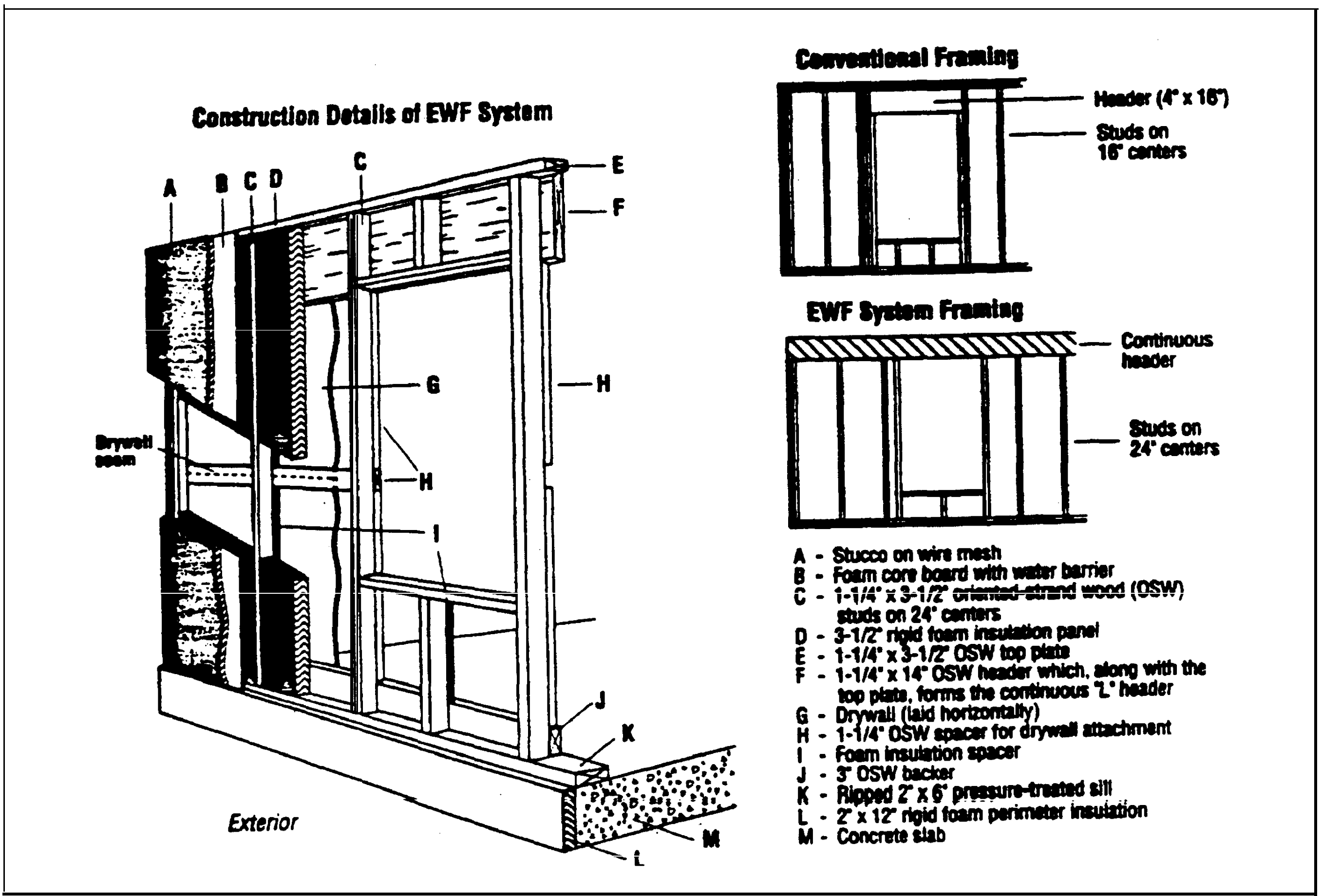

Figure 3. Engineered Wall Framing

remaining packages, included the siting and form (reduced perimeter and reduced, well-placed glazing) and envelope improvement EEMs (EWF and vinyl window frames) was completed. Packages 1 and 3 were economically practical and offered the potential for 59% and 60% overall savings respectively. Package #4 became technically and economically practical when a "cooling elimination" sub-package (EEMs which were not individually cost effective) was added and credited with the capital cost of eliminating the last of the conventional cooling system. This sub-package consisted of:

- increased tile floor area,
- ceiling fans,
- attic radiant barrier,
- whole house fan,
- double drywall in the living space,
- low-E gas filled glazing,
- insulated doors

Package 4 which had projected savings of 62% was selected for the Davis site because it was felt that the Davis market would be an ideal environment for testing a fully engineered "non-cooling" package.

Table 1. Building Envelope Thermal Performance

Building Envelope	Davis Btu/hr-ft^2-°F	Stanford Ranch Btu/hr-ft^2-°F
Glazing overall U-value	0.28	0.42 (0.26)[(a)]
Wall overall U-value	0.039	0.039
Roof overall U-value	0.022	0.026
Door overall U-value	0.091	0.091

(a) Southwest glazing

At Stanford Ranch a different set of three strategies were identified due to the more severe climate, they were:

1) forced air heating and compressor based cooling

2) radiant floor heating and indirect/direct evaporative cooling

3) radiant floor heating and ventilative cooling

The design team presented the three packages to the builder who, acting on the customer's behalf, recommended a veto of package #3, which offered total savings of 66%, because it was felt that the average home owner would require on demand cooling. Package #2, which had projected overall savings of 65%, was eliminated when the City Building Department required a heat exchanger and circulating pump be installed in the hydronic system; thereby, reducing efficiency and introducing a parasitic load. At this point, a fourth strategy was developed:

4) forced air hydronic heating and direct evaporative cooling with below slab night storage

This strategy takes advantage of the greatly increased efficiency of evaporative cooling during off peak periods. Water is chilled to 60°F at night and stored under the slab in 1000 feet of 2 inch plastic tubing. Since normal ground temperature below a slab during the summer is 60°F thermal storage is achieved with relatively little cost. The majority of cooling energy is delivered passively through the slab. However, during peak cooling periods when the thermostat calls for cooling, water is pumped from below the slab to a fan coil air handler and cool air is delivered to the interior spaces. Package 4 had projected overall savings of 64% and reduced peak cooling demand by 4.4 Kw.

All packages for both houses included extensive use of compact fluorescent lighting with electronic ballasts, high efficiency dishwashers, and horizontal axis clothes washers and many other small space and non-space conditioning EEMs. The Davis site design incorporated a SunFrost refrigerator and a combined refrigerator water heater (CREWH) system to preheat domestic hot water. The Stanford Ranch site was equipped with one of the first refrigerators from the Super Efficient Refrigerator Program (SERP).

Final Design

The Davis Site design consists of 26 EEMs (see Table 2) having a projected 62% overall energy savings, with a life cycle cost savings of $3,673 using mature market economics. Projected energy use comparisons are listed in Table 3.

The Stanford Ranch design incorporates 28 EEMs (see Table 4) into an integrated package, that is projected to improve total energy efficiency by 64%, at an additional life cycle cost of $278 (using mature market economics) over the basecase. Projected energy use comparisons are listed in Table 5.

Construction

Construction and commissioning of the Davis site was completed in December 1993. The house was built with few changes from the design. Of note was the fact that the SunFrost refrigerator was not acceptable to the home owners because of its size. A somewhat less efficient conventional refrigerator had to be substituted and modified to incorporate the CREWH system. The design had assumed a indoor temperature of 68°F, however, the home owners are maintaining a thermostat setting of 70°F. This will affect the projected performance and must be taken into account when evaluating the design performance.

Construction and commissioning of the Stanford Ranch site was completed in May of 1994. The EWF system installed at Stanford Ranch differs from the Davis site installation due to Stanford Ranch's ceiling heights and improvements that were made as a result of the Davis site experience. For structural strength the 1-1 /4 by 3-1/2 inch studs were replaced by 1-1/4 by 4-3/4 inch studs on 24 inch centers, the 1-1/4 inch air space was maintained. The 1-1/4 by 16 inch continuous header was replaced with a double top plate and 1-1/4 by 16 inch headers over doors and window openings only. The interior 1-1/4 foam spacers were eliminated to save labor. An inch of Styrofoam insulation sheathing was added to the exterior of the framing behind the stucco. These changes resulted in a wall system that is less expensive to construct than the Davis site wall system and increased thermal efficiency to a calculated R-29.

Conclusions

The first year monitoring results will be available in January 1995 for the Davis site and July 1995 for the Stanford Ranch site. Conclusions on the performance of the designs will be drawn after the monitored data is reviewed and analyzed.

Endnote

1. The cost-of-conserved energy (CEE) is the sum of the present value of the cost, times the capital recovery factor, divided by the first year energy savings. The capital recovery factor converts a present-year lump sum cost to equal annual payments using an interest

Table 2. Davis Site Sequential EEM Order

		Economics Summary		Annual Energy Savings		
				Annual Savings		
#	**Description**	**NPV/BCR (1)**	**LCC (2)**	**therms**	**kWh**	**Cumm. %**
1	Schematic Design	$5,198	-4347	101.0	231	12
2	High R Window Frames	$397	-298	13.3	17	13
3	Roof Surface Char.	$130	-76	-4.4	86	13
4	Engineered Wall Framing	$677	-456	38.5	-11	17
5	Radiant Subpackage	$1,439	-154	167.7	247	35
6	Low Flow Showerheads	$63	0	10.1	0	36
7	High Efficiency Exhaust Fans	$11	0	0.0	12	37
8	Anti-Convection Valves	11.7	4	6.7	0	37
9	High Efficiency Clothes Washer	3.6	37	14.0	32	39
10	Parallel Piping	2.8	5	2.8	0	39
11	PTV Improvements	2.8	6	2.8	0	39
12	Low Flow Lavatories	2.2	19	6.7	0	40
13	Level II Lighting Improvements	2.0	50	0.0	107	41
14	High Efficiency Refrigerator	1.9	592	-13.2	1266	50
15	Level I Lighting Improvements	1.5	650	-5.0	1062	57
16	Improved Oven	1.2	9	1.7	0	58
17	Extra DHW Tank Insulation	1.1	25	4.4	0	58
18	Refrigerator Water Heater	1.0	138	18.0	18	60
19	Cooling Elimination Subpackage	0.7	292	7.4	161	62
20	Efficient Dryer Motor	0.7	63	0.0	46	62
	Total			372.5	3274	62%

Notes:
(1) NPV listed for EEM's with infinite BCR's.
(2) Life Cycle Cost.

Table 3. Davis Site Projected Energy Use Comparison by Function

	Base Case Use		Package Use		
	kWh	**therms**	**kWh**	**therms**	**Package Savings**
Heating	115	275	61	57	78%
Cooling	796	0	0	0	100%
DHW	0	189	20	38	79%
Lights & Refr.	3051	0	847	0	72%
Other	2034	75	1910	72	5%
Total	5996	539	2838	167	62%

Table 4. Stanford Ranch Site Sequential EEM Order

		Economics Summary		Annual Energy Savings		
				Annual Savings		
#	Description	NPV/BCR (1)	LCC (2)	therms	kWh	Cumm. %
1	Schematic Design	$2,731	-2142	62.1	207	7
2	Engineered Wall Framing	$509	-82	67.7	2	12
3	Low Flow Showerheads	$66	0	10.0	3	13
4	Light Colored Wall Surface	$48	-17	-2.5	48	13
5	Insulated Doors	$19	0	4.8	-12	14
6	High Efficiency Exhaust Fans	$9	0	0.0	12	14
7	Water Heater Relocation	$8	0	1.3	0	14
8	Tuned Glazing: Southwest Low-E Cooling	58.5	2	-4.8	129	14
9	Combined Hydronic Heating	2.2	283	1200.7	-13	23
10	Anti-Convection Valves	9.2	4	5.1	0	23
11	Improved Ducts	8.9	76	33.4	500	29
12	Argon Fill (Clear Glass)	7.3	5	13.7	-53	30
13	High Efficiency Refrigerator	1.4	822	-9.2	1261	38
14	Evaporative Underfloor Cooling with Forced Air Delivery	5.4	259	0.0	1498	48
15	Outdoor Light Motion Sensor	4.6	49	0.0	239	50
16	Parallel Piping	3.9	6	3.7	0	50
17	High Efficiency Clothes Washer	3.7	33	13.9	34	52
18	Level I Lighting Improvements	2.3	382	-9.4	984	57
19	PTV Improvements	1.7	9	2.4	0	58
20	Low Flow Fixtures	1.6	30	7.7	0	58
21	Dryer Heat Recovery	1.6	27	5.9	6	59
22	High Efficiency Blower Motor and Fan	1.4	87	7.6	83	60
23	Level II Lighting Improvements	1.3	141	-2.0	212	61
24	Extra Water Heater Tank Insulation	1.1	25	4.4	0	62
25	Added Oven Insulation	1.1	9	-0.1	12	62
26	High Efficiency Dishwasher	1.1	73	6.1	42	62
27	Slab Edge Insulation	0.9	134	19.2	3	64
28	High Efficiency Dryer Motor	0.7	63	-0.4	46	64
	Total			341.3	5244	64%

Table 5. Stanford Ranch Site Projected Energy Use Comparison by Function

	Base Case Use		Package Use		
	kWh	**therms**	**kWh**	**therms**	**Package Savings**
Heating	138	312	65	86	72%
Cooling	2679	0	259	0	90%
DHW	0	160	0	52	68%
Lights & Refr.	3392	0	798	0	76%
Other	2655	0	2513	0	5%
Total	8864	472	3635	138	64%

rate. The energy savings are in either kWh or Therms—if electricity savings are greater, then the value will be in units of kWh; otherwise, the value will be in units of Therms. Conversion from kWh to Btu is performed using the utility's average heat rate.

References

PG&E. 1990. *Facts on ACT*[2]. Issue 1-6, October 1990, January 1991, March 1991, July 1991, September 1991, February 1992. PG&E Research and Development Department, San Ramon, California.

Meier, A. K. 1982, "Supply Curves of Conserved Energy." LBL-14686 May 1982, Lawrence Berkeley Laboratory, Berkeley, CA.

Lawrence Berkeley Laboratory. *1989. DOE-2 Supplement, Version 2.1E,* LBL-8706 Suppl. Rev. 6, June 1991. National Technical Information Service, Springfield, Virginia.

[CEC] California Energy Commission. 1988. California Code of Regulations Title 24—Building Energy Efficiency Standards. Sacramento, CA.

Boume, R. C. 1994. "Sequential Analysis and Packaging of Energy Efficiency Measures." Energy Efficiency Improvements–Proceedings from DA DSM 94 pp.426-436. DA DSM 94, Orlando, FL.