December 1999 • NREL/JA-550-25914

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Article as Submitted to the ASHRAE Journal
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Prepared under Task No. BE00.4001

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Sixty-Three Percent Energy Cost Savings Achieved through Low-Energy Design Process

Buildings designed and constructed using an energy design process that optimizes the interaction between the building envelope and systems can save between 30% and 75% in energy costs. These buildings can be constructed for the same or nearly the same first cost as a non energy-efficient building with no sacrifice of comfort or functionality. First, the energy design process requires that a design team be committed to energy efficiency before the pre-design phase. Detailed computer simulations are then used throughout the design and construction phases to ensure the building's optimal energy performance and that changes to the design do not adversely affect that performance. Properly commissioning the building and educating the building operators are the final steps in the design process to successfully construct a low-energy building.

This energy design process was used to design and construct the Thermal Test Facility (TTF) at the National Renewable Energy Laboratory (NREL). The TTF is a 10,000-ft^2 (929-m^2) office and light laboratory building constructed in 1996 in Golden, Colorado. Actual performance data collected for more than one year show that the TTF costs 63% less to operate than an equivalent building which complies with ASHRAE Standard 90.1.

DESIGN PROCESS

To successfully realize a low-energy building, the design team, which consists of the owner, architect, and engineer, must make cost-effective energy minimization a high priority design goal. The team must work closely together throughout the design and

construction phases to ensure this goal is met. Low-energy design is not intuitive. The energy use and energy cost of a building depends on the complex interaction of many parameters and variables that can only be effectively evaluated with hourly building energy simulation tools. Therefore, it is important that at least one member of the design team acts as the energy consultant. This person helps guide design decisions by evaluating all design strategies using the computerized design tools.

SIDEBAR — 9-step process for low-energy building design

1) Create a base case building model to quantify base case energy use and costs. The base case building is solar neutral (equal glazing areas on all wall orientations) and meets the requirements of applicable energy efficiency codes such as ASHRAE Standard 90.1 and 90.2.
2) Complete a parametric analysis to determine sensitivities to specific load components. Sequentially eliminate loads from the base case building, such as conductive losses, lighting loads, solar gains, and plug loads.
3) Develop preliminary design solutions. The design team brainstorms possible solutions that may include strategies to reduce lighting and cooling loads by incorporating daylighting or to meet heating loads with passive solar heating.
4) Incorporate preliminary design solutions into a computer model of the proposed building design. Energy impact and cost effectiveness of each variant is determined by comparing the energy with the original base case building and to the other variants. Those variants having the most favorable results should be incorporated into the building design.

5) Prepare preliminary set of construction drawings. These drawings are based on the decisions made in step 4.
6) Identify an HVAC system that will meet the predicted loads. The HVAC system should work with the building envelope and exploit the specific climatic characteristics of the site for maximum efficiency. Often, the HVAC system is much smaller than in a typical building.
7) Finalize plans and specifications. Ensure the building plans are properly detailed and that the specifications are accurate. The final design simulation should incorporate all cost-effective features. Savings exceeding 50% from a base case building are frequently possible with this approach.
8) Rerun simulations before design changes are made during construction. Verify that changes will not adversely affect the building's energy performance.
9) Commission all equipment and controls. Educate building operators. A building that is not properly commissioned will not meet the energy efficiency design goals. Building operators must understand how to properly operate the building to maximize its performance.

Table 1 outlines the assumptions made in the TTF base case model and the final design decisions made for the TTF construction. The base case model complies with the Federal Energy Code 10CFR435, which is based on ASHRAE Standard 90.1.

Table 1. Base Case Assumptions and Final TTF Construction

Design Category	Base Case Assumption	Final TTF Construction
Forced ventilation rate	15 cfm/person (7 l/s/person) during occupied hours	15 cfm/person (7 l/s/person) during occupied hours
Natural infiltration rate	0.25 ACH during unoccupied hours	0.1 ACH during unoccupied hours
Lighting levels	1.4 W/ft^2 (15.1 W/m^2) during occupied hours	0.80 W/ft^2 (8.6 W/m^2)
Wall R-value	R-10.6 hr·ft^2·°F/Btu (1.8 m^2·K/W) (batt insulation between the studs and exterior polystyrene insulation)	North wall (tilt-up concrete): R-10.3 hr·ft^2·°F/Btu (1.8 m^2·K/W) (exterior polystyrene insulation) Other walls (steel stud): R-23 hr·ft^2·°F/Btu (4.0 m^2·K/W) (batt insulation between the studs and exterior polystyrene insulation)
Floor R-value	R-10.6 hr·ft^2·°F/Btu (1.8 m^2·K/W) perimeter insulation	R-10.6 hr·ft^2·°F/Btu (1.8 m^2·K/W) perimeter insulation
Roof R-value	R-19 hr·ft^2·°F/Btu (3.3 m^2·K/W)	R-23 hr·ft^2·°F/Btu (4 m^2·K/W)
Window U-value	U-0.55 Btu/hr·ft^2·°F (3.1 W/m^2·K)	U-0.33 Btu/hr·ft^2·°F (2.4 W/m^2·K)
Window solar heat gain coefficient	All windows: SHGC = 0.78	Clerestory windows: SHGC = 0.68 All others: SHGC = 0.45

DAYLIGHTING STRATEGY

The pre-design base case analysis predicted the TTF's largest energy consumption would be the lighting (Figure 1). As a result, the majority of the building was designed to be daylit. Daylighting and efficient lighting technologies eliminated 75% of the predicted lighting energy consumption (Figure 2). The building contains no security lighting. The interior lights turn on when the occupancy sensors detect motion within the building, eliminating the need for 24-hour security lighting. It is estimated that not operating 10% of the electrical lighting 24 hours/day saves 2630 kWh/year.

See Figure 1. Cost Breakdown Comparison

See Figure 2. Lighting Cost Comparison

The TTF uses either T-8 fluorescent fixtures with electronic ballasts or compact fluorescent fixtures. Daylighting/occupancy sensors control all electrical lighting. The

sensors in the daylit spaces are on a single-step control system; the lights are either on or off. Dead-band set points and operating periods have been tuned to prevent excessive cycling during periods of partial cloud cover; however, photo sensor control remains a weak point in most daylighting systems. Although continuous lighting controls with dimming lights would save an additional 6%, this technology was not cost-effective at the time of design (1994).

ENERGY-EFFICIENT BUILDING ENVELOPE

The TTF's thermal envelope provides a good insulating shell and incorporates features that benefit daylighting and passive solar heating and cooling strategies (See Table 1). Overhangs above the clerestories were engineered to prevent direct solar gain during the cooling months yet permit solar gains during the winter for passive solar heating. Overhangs and side fins around the ground-level windows prevent solar gains for most of the year to improve the thermal comfort of the occupants working near these windows. East-/west-facing window were minimized to prevent overheating from solar gains. North-facing windows were optimized so that the benefits from daylighting outweighed the disadvantages from heat loss. The stepped roof design allowed placement of clerestory windows at two locations to increase daylighting and passive solar winter gains. Clerestory windows have high shading coefficients to increase the solar gain transmittance during the winter months when these windows are not shaded. Trade-off analyses were made to select the proper glass to maximize solar gain and daylighting. All windows are low-e and have low U-values.

HVAC SYSTEM LOADS AND OPERATION

While the use of electrical lights in most commercial buildings help provide heat, they also have a negative impact on a building's cooling demand. With daylighting, the lights no longer heat the space. The lower internal gains resulted in increasing the TTF's heating load costs by 5% compared to the base case, despite large winter solar gains, and cooling load costs decreased by approximately 43%. Properly sizing the overhangs and side fins and minimizing east- and west-facing windows also contributed to reducing the cooling load and the size of this equipment. The building HVAC system was sized based on the loads that were calculated after daylighting, an efficient lighting system, and a good thermal envelope were incorporated into the design.

The TTF usually requires heating only during the early morning hours to compensate for the nightly temperature set back. Although the temperature is set back to 55°F (13°C) every night during the heating season, the temperature does not drop that low. During the morning warm up, the temperature is increased to 70°F (21°C). After the morning warm up, passive solar heating and internal gains meet most of the building's heating requirements.

The energy required to operate the air-conditioning system was reduced by using a two-stage evaporative cooling system instead of a conventional chilled-water or direct-expansion cooling system. In the dry Denver climate, the indirect portion of the evaporative cooler is able to supply air at 70°F DB/49°F WB (21°C DB/9°C WB) on a design day, 95°F DB/59°F WB (35°C DB/15°C WB). Operating the direct portion of the evaporative cooler reduces the supply air temperature further to 56°F DB/49°F WB (13°C DB/9°C WB).

Another option for cooling the building was with chilled water from a chilled water plant. Because this system was not used, the chilled water distribution pumps were not needed. The total building pump energy cost was then reduced by 73% (remaining pumps are for hot water coils) compared to the base case.

Fan energy requirements increased by implementing the evaporative cooling system versus a more conventional system. However, the savings from the evaporative cooling system far outweighed the increased fan energy requirements.

Other innovative HVAC system features were also included in the TTF. Short duct runs minimize duct static pressure and reduce fan size. Thermostatically controlled ceiling fans eliminate stratification and distribute conditioned air and ventilation air throughout the building. Air-to-air heat exchangers condition ventilation air. Fan-powered VAV units with hot-water coils meet most heating loads without running the main air handling unit. An energy management system (EMS) operates all mechanical and lighting systems.

Figure 3 shows the cost for operating both the base case building HVAC system and the TTF HVAC system. The following trends shown in this figure include:

1) The cooling costs are reduced as a result of evaporative cooler efficiency and the reduction of internal and solar gains.
2) Pump operating costs are reduced because the base case chilled water pumps were eliminated.
3) The total heating load is increased slightly because the electrical lights no longer heat the building.

4) The benefits from the passive solar strategies are the greatest in December and January.

See Figure 3. Monthly HVAC Costs Comparison

CONCLUSIONS

Reducing the operating costs of the TTF by 63% compared to a code-compliant building was achieved by following an energy design process from the conceptual design phase through the building commissioning phase. Communication between all members of the design team from the start of the design process ensured the design of the building envelope and internal systems were integrated as a single unit.

Although the TTF was designed as a laboratory building, the technologies discussed in this paper can be applied to other commercial buildings, such as retail buildings, office buildings, and warehouses. The strategies used for the TTF are an innovative application of technologies currently available to the U.S. building industry. Each feature is part of an integrated design. No one design feature can be added or deleted without affecting other elements of the whole-building package.

ACKNOWLEDGMENTS

The energy design and evaluation of this building is part of the National Renewable Energy Laboratory (NREL) Low-Energy Buildings Research Project. The U.S. Department of Energy (DOE) Office of Building Technology, State and Community Programs, Commercial Buildings Research provides project funding. Mary-Margaret Jenior is the DOE Program Manager for the project. Additional information about the TTF and the Low-Energy Buildings Research Project can be found on

www.NREL.gov/buildings/highperformance and information about DOE can be found on www.eren.doe.gov.

The architect for the project was Jim Copeland of Abo-Copeland Architects in Denver, Colorado. The project mechanical engineer was Charles Fountain of Burns and McDonnell also in Denver. The construction manager was Bruce Field of NREL in Golden, Colorado. Michael S. Ketcham, a Ph.D. student with the University of Colorado completed monitoring and data analysis of the TTF. Otto van Geet is the lead mechanical engineer for NREL Site Operations and was responsible for design review. Ron Judkoff of NREL developed initial solar and low-energy design concepts. Stephen Ternoey of LightForms – Architectural Daylighting, Lighting, and Energy Consultants developed the initial daylighting concepts. Paul Torcellini of NREL led the simulation and energy cost optimization effort.

SIDEBAR — TTF Project Details

Project Description: Research and Office Building
Size: 1 story with high-ceiling bays, 10,000 square feet (929 m^2)
Location: Golden, Colorado
Heating Degree-Days: 6020
Cooling Degree-Days: 679
Construction Cost: $1,127,000
Date Completed: June 1996

ENERGY PERFORMANCE

The total actual energy consumption for the TTF is 20,600 Btu/ft^2/yr (234 million joules/m^2/yr). The estimated total for the base case is 40,600 Btu/ft^2/yr (461 million joules /m^2/yr). The reduction is about 50%. The energy cost savings for the TTF is 63%.

The chart below provides a comparison of the TTF actual annual energy costs and the predicted costs for the modeled base case, designed to meet ASHRAE Standard 90.1. The chart does not show water heating, external lighting and pump costs, which combined are less than 4% of the total. The chart also does not include office and lab equipment loads, which are determined by occupant use not building design.

	Reference	TTF	Percent Change
Lighting	$4205	$1050	- 75 %
Cooling	$ 850	$ 485	- 43 %
Space Heating	$ 415	$ 435	+ 5 %
Total	$5470	$1970	- 64 %

Auxiliary HVAC System: Variable air volume (VAV) system with hot water coils and a direct/indirect evaporative cooler (including an economizer cycle). The system also includes thermostatically controlled ceiling fans and heat recovery units.

SOLAR/DAYLIGHTING FEATURES*

- High aspect ratio (east/west axis is twice as long as north/south axis)
- 85% of the total glazing faces south. Ground-level windows account for 490 ft^2 (45.5 m^2) of glazing and clerestories account for 598 ft^2 (55.6 m^2)
- All windows are high-performance low-e windows. Clerestories have a high shading coefficient
- Direct solar gain for heating afforded by clerestories
- Thermal mass in form of externally-insulated concrete wall on north side and slab-on-grade concrete floor

- Open floor plan
- Electric lighting integrated with daylighting

ENERGY EFFICIENCY FEATURES*

- R-19 roof (3 inches [7.5 cm] of polyisocyanurate under a metal deck)
- R-23 walls (6-inch [15-cm] metal studs, fiberglass batts, 1.5 inches [3.8 cm] external polystyrene)
- T-8 fluorescent ceiling lamps and electronic ballasts, compact fluorescent can fixtures
- Occupancy sensors and daylight sensors
- Economizer cycle and direct/indirect evaporative cooling
- High-efficiency motors and variable speed drives
- Advanced computer-controlled energy management system

*Note: While solar and efficiency features are listed here, each feature is part of an integrated design. No one design feature can be added or deleted piecemeal without affecting other elements of the whole-building package.

COST PERFORMANCE

Additional expenses related to daylighting and other features that enhance energy performance total about $40,000. Savings on construction cost related to the energy-efficient design total about $15,000. The difference – $25,000 in added expenses (about 2% of the total building budget) – is recouped in about 7 years of saving $3500 per year on energy bills

ENVIRONMENTAL/HEALTH FEATURES

- Continuous ventilation system to control air quality and humidity
- Daylighting
- Xeriscaping to conserve water

The large reduction in electricity consumption reduces the air pollution impacts of power production. The following emissions are avoided each year:

- 79,600 lb. of CO_2
- 460 lb. of SO_2
- 240 lb. of NO_x

AUTHORS' NOTES

Sheila J. Hayter, P.E., ASHRAE member, is a research engineer for the Low-Energy Buildings Research Project at the National Renewable Energy Laboratory (NREL), Golden, Colorado. She also leads the NREL Photovoltaics for Buildings activities. Sheila currently chairs the ASHRAE Continuing Education Committee and TC 9.1, "Large Building Air-Conditioning System." She is also vice chair of TC 1.10, "Energy Resources."

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Ron Judkoff, ASHRAE member, is the Director of the Center for Buildings and Thermal Systems at NREL, Golden, Colorado. Ron currently chairs ASHRAE SPC140 "Standard Method of Test for Building Energy Software." He is on the technical review committees for ASHRAE research projects 865 and 1052. He has been a voting member and is now an active corresponding member of TC 4.7, "Energy Calculations."

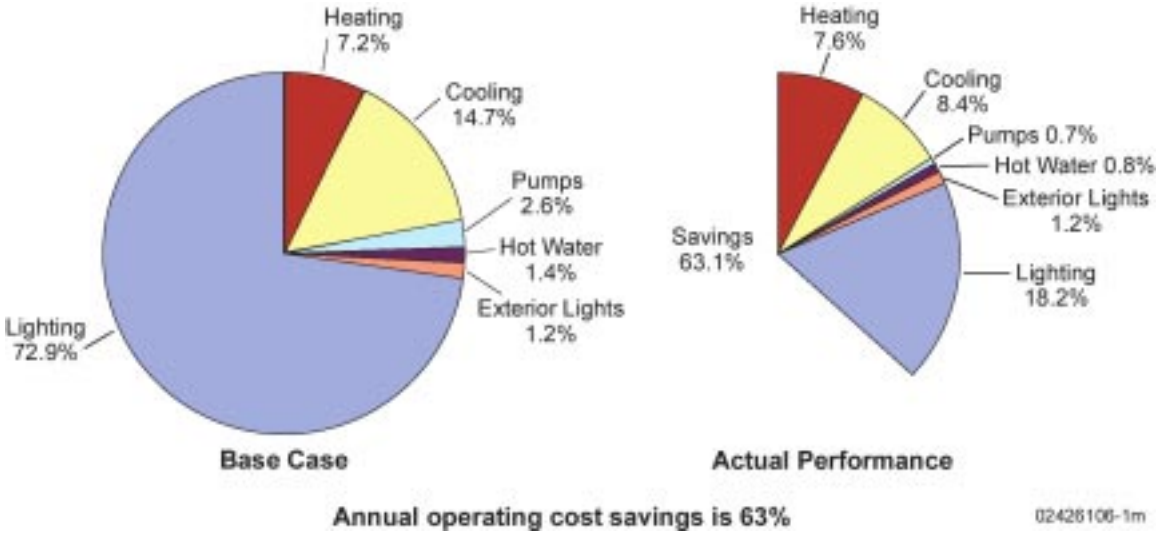

Figure 1. Cost breakdown comparison. Annual operating cost saving is 63%.

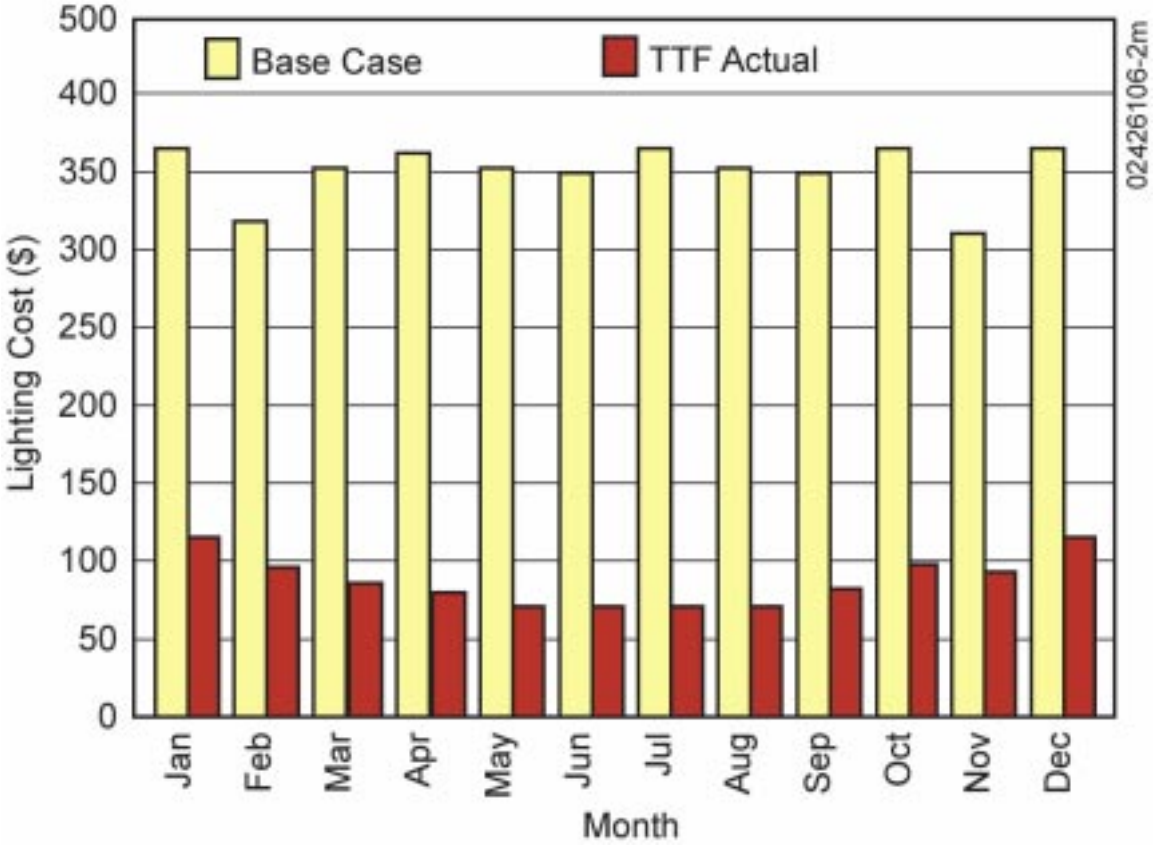

Figure 2. Lighting cost comparison.

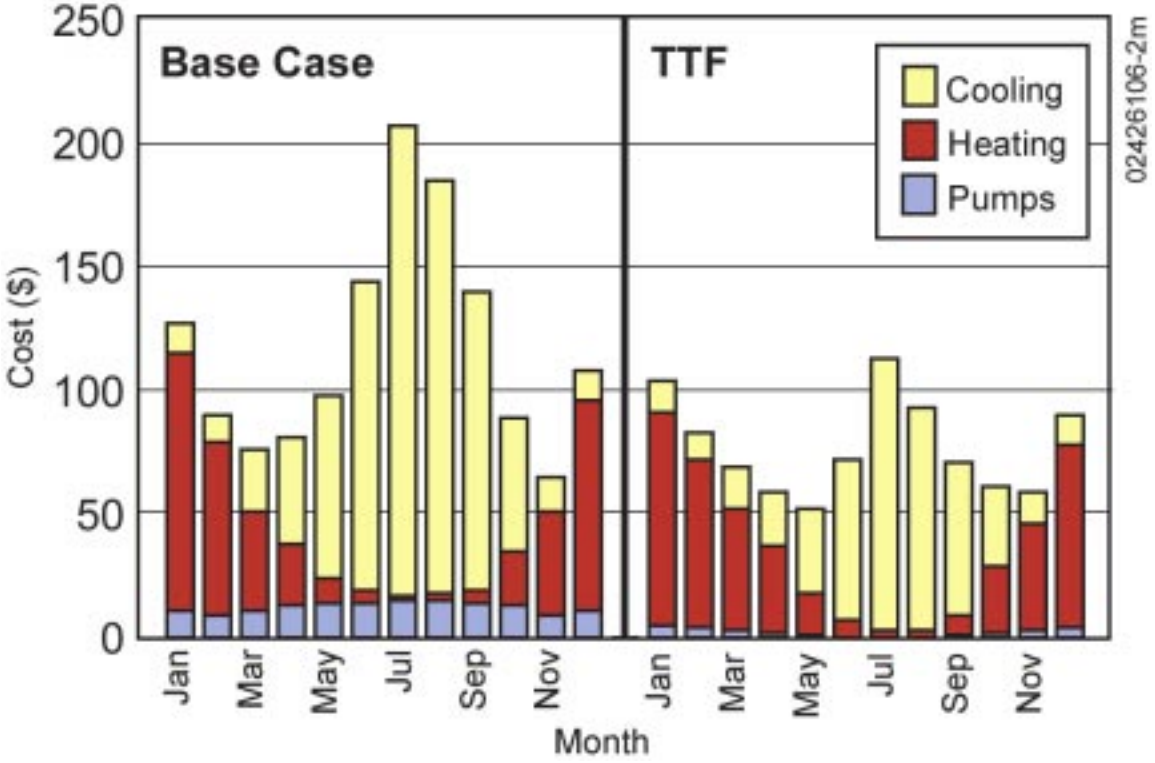

Figure 3: Monthly HVAC costs comparison.

Cover Photo: View of TTF showing south clerestories.

Notes:

1. This document is the draft prior to publication by ASHRAE. Some material was removed from this document prior to publication.
2. Hayter, S., Torcellini, P., Judkoff, R. "Optimizing Building and HVAC Systems," ASHRAE Journal, December 1999, American Society of Heating Refrigerating, and Air-conditioning Engineers, Atlanta.