

DTIC FILE COPY



US Army Corps
of Engineers

Construction Engineering
Research Laboratory

USA-CERL TECHNICAL REPORT E-89/04

January 1989

FEAP: Ceiling Fan Energy and Comfort Demonstration

2

AD-A203 143

An Evaluation of the Effectiveness of Ceiling Fans for Reducing Heating Requirements in Army Facilities

by
Lawrence J. Augustine

Many claims have been made for ceiling fans as energy saving devices. Fans destratify the air in a building; that is, they reduce the temperature differences between floor and ceiling. Depending on outside conditions, this can reduce heat loss. To quantify the effectiveness of fans during the heating season, USA-CERL, funded through a Facilities Engineering Applications Program (formerly FTAT) project, collected vertical thermal stratification measurements in Army buildings that had been equipped with ceiling fans. The buildings were located at Fort Carson, CO and Fort McClellan, AL. By analyzing how much the key building temperatures (ceiling, floor, and mean indoor) changed when ceiling fans were used, the USA-CERL engineers estimated the energy savings associated with fans.

The results showed that, in general, the buildings with the greatest initial stratification showed the greatest savings. In addition, the degree of thermal stratification was determined to be a linear function of outside air temperature. However, more research is needed to determine the relationship between stratification and building characteristics. Thus, the degree of stratification in a building and possible factors affecting it should be evaluated carefully before installing ceiling fans.

DTIC
SELECTED
31 JAN 1989
E

Approved for public release; distribution is unlimited.

89 1 30 146

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE				Form Approved OMB No 0704 0188 Exp Date Jun 30 1986	
1a REPORT SECURITY CLASSIFICATION Unclassified		1b RESTRICTIVE MARKINGS			
2a SECURITY CLASSIFICATION AUTHORITY		3 DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution is unlimited.			
2b DECLASSIFICATION/DOWNGRADING SCHEDULE		5 MONITORING ORGANIZATION REPORT NUMBER(S)			
4 PERFORMING ORGANIZATION REPORT NUMBER(S) USA-CERL TR E-89/04		7a NAME OF MONITORING ORGANIZATION			
6a NAME OF PERFORMING ORGANIZATION U.S. Army Construction Engr Research Laboratory		6b OFFICE SYMBOL (if applicable) CECER-ES	7b ADDRESS (City, State, and ZIP Code)		
6c ADDRESS (City, State, and ZIP Code) P.O. Box 4005 Champaign, IL 61820-1305		9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER FTAT-ES-FG7			
8a NAME OF FUNDING/SPONSORING ORGANIZATION USAHSC		8b OFFICE SYMBOL (if applicable) CEHSC-FU	10 SOURCE OF FUNDING NUMBERS		
8c ADDRESS (City, State, and ZIP Code) Fort Belvoir, VA 22060		PROGRAM ELEMENT NO	PROJECT NO	TASK NO	WORK UNIT ACCESSION NO
11 TITLE (Include Security Classification) An Evaluation of the Effectiveness of Ceiling Fans for Reducing Heating Requirements in Army Facilities (U)					
12 PERSONAL AUTHOR(S) Augustine, Lawrence J.					
13a TYPE OF REPORT final		13b TIME COVERED FROM _____ TO _____		14 DATE OF REPORT (Year, Month, Day) 1989, January	15 PAGE COUNT 23
16 SUPPLEMENTARY NOTATION Copies are available from the National Technical Information Service Springfield, VA 22161					
17 COSATI CODES			18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)		
FIELD	GROUP	SUB-GROUP			
10	01		ceiling fans energy consumption ventilation fans heating		
19 ABSTRACT (Continue on reverse if necessary and identify by block number)					
<p>Many claims have been made for ceiling fans as energy saving devices. Fans destratify the air in a building; that is, they reduce the temperature differences between floor and ceiling. Depending on outside conditions, this can reduce heat loss. To quantify the effectiveness of fans during the heating season, USA-CERL, funded through a FEAP project, collected vertical thermal stratification measurements in Army buildings that had been equipped with ceiling fans. The buildings were located at Fort Carson, CO and Fort McClellan, AL. By analyzing how much the key building temperatures (ceiling, floor, and mean indoor) changed when ceiling fans were used, the USA-CERL engineers estimated the energy savings associated with fans.</p>					
(Cont'd.)					
20 DISTRIBUTION AVAILABILITY OF ABSTRACT <input type="checkbox"/> UNCLASSIFIED/UNLIMITED <input checked="" type="checkbox"/> SAME AS RPT <input type="checkbox"/> DTIC USERS			21 ABSTRACT SECURITY CLASSIFICATION Unclassified		
22a NAME OF RESPONSIBLE INDIVIDUAL Dana Finney			22b TELEPHONE (Include Area Code) (217) 352-6511 ext 389	22c OFFICE SYMBOL CECER-IMT	

UNCLASSIFIED

Block 19. (Cont'd.)

The results showed that, in general, the buildings with the greatest initial stratification showed the greatest savings. In addition, the degree of thermal stratification was determined to be a linear function of outside air temperature. However, more research is needed to determine the relationship between stratification and building characteristics. Thus, the degree of stratification in a building and possible factors affecting it should be evaluated carefully before installing ceiling fans.

UNCLASSIFIED

FOREWORD

This work was performed for the U.S. Army Engineering and Housing Support Center (USAEHSC) under Project FTAT-ES-FG7, "Ceiling Fan Energy and Comfort Demonstration." Mr. B. Wasserman, CEHSC-FU, was the Technical Monitor.

The work was performed by the Energy Systems Division, U.S. Army Construction Engineering Research Laboratory (USA-CERL-ES). Dr. G. Williamson is Chief, USA-CERL-ES.

COL Carl O. Magnell is the Commander and Director of USA-CERL, and Dr. L. R. Shaffer is the Technical Director.

Accession For	
NTIS GRA&I	<input checked="" type="checkbox"/>
DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
By _____	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A-1	



CONTENTS

	Page
DD FORM 1473	1
FOREWORD	3
LIST OF TABLES AND FIGURES	5
1 INTRODUCTION	7
Background	
Objective	
Approach	
Scope	
Mode of Technology Transfer	
2 ENERGY SAVINGS CALCUATIONS.....	9
Building Descriptions	
Estimated Building Heat Loss Values	
Temperature Data	
Estimated Savings	
3 STRATIFICATION AND OUTDOOR AIR TEMPERATURE.....	18
4 CONCLUSIONS AND RECOMMENDATIONS	22
DISTRIBUTION	

TABLES

Number	Page
1 Building Descriptions, Fort Carson	10
2 Building Descriptions, Fort McClellan	11
3 Heat Loss Parameters for Demonstration Buildings	12
4 Reduction in Key Temperatures (°F), Fort Carson	13
5 Reduction in Key Temperatures (°F), Fort McClellan	14
6 Estimated Energy Savings From Ceiling Fan Operation	15
7 Annual Dollar Savings From Ceiling Fan Operation	17
8 USA-CERL Highbay Temperature Data	19

FIGURES

1 Results of Regression Analysis, USA-CERL Highbay	19
2 Results of Regression Analysis, Fort Carson Motor Pool, Bldg 633	20
3 Results of Regression Analysis, Fort Carson Gym, Bldg 2357	21
4 Results of Regression Analysis, Fort Carson Gym, Bldg 1856	21

AN EVALUATION OF THE EFFECTIVENESS OF CEILING FANS FOR REDUCING HEATING REQUIREMENTS IN ARMY FACILITIES

1 INTRODUCTION

Background

Ceiling fans have been promoted for several years as energy conservation devices. Substantial savings are claimed--as much as 30 percent by one manufacturer.¹ However, limited documentation exists on measured savings obtained by operating ceiling fans or other destratification devices. For Army installations to best use ceiling fans in meeting their energy goals, such claims need to be verified.

Fans destratify the air in a room or building by giving it velocity, thus creating a more uniform temperature distribution from floor to ceiling. Where thermal stratification has occurred in a room, air temperatures increase from floor to ceiling. The average air temperature in a stratified room with tall ceilings is higher than the temperature experienced by the room occupants. In the heating season, stratification results in a greater heat loss through the building envelope than when there is a uniform temperature distribution. In contrast, during the cooling season, stratification is beneficial: it reduces the heat gain through the ceiling and upper walls of a building. Since temperatures at the occupant level are lower than the average room temperature, a cooling system does not need to maintain a uniform temperature distribution to keep occupants comfortable.

Promoters of ceiling fans claim savings for both the heating and cooling seasons. Any savings realized during the heating season would arise from the differences in heating requirements between a stratified room and the same room with a uniform temperature distribution. Summer savings would result from the cooling effect that moving air has on human occupants: comfort could be maintained at a higher thermostat setting. However, limited documentation exists on measured savings obtained by operating ceiling fans or other destratification devices.

Objective

The objectives of this investigation were to (1) demonstrate the energy saving potential of using ceiling fans to reduce heating requirements, (2) correlate outdoor temperature to the degree of stratification within structures, and (3) determine the best facilities for the application of ceiling fans.

Approach

USA-CERL installed ceiling fans in a total of 10 buildings located at Fort Carson, CO and Fort McClellan, AL. The fans were installed according to the manufacturer's

¹Envirofans: The Climate Control System, manufacturer's literature, Envirofan Systems, Inc., Buffalo, NY, October 1984.

recommendations for the number and location of fans. Temperature stratification measurements were taken in these buildings. As-built drawings and engineering handbooks were used to estimate building heat transfer characteristics. Measured changes in the ceiling, floor, and mean temperatures as a result of ceiling fan operation were used to determine the magnitude of energy savings.

Scope

The data and conclusions in this report apply only to the heating season. Entirely different processes occur in the cooling season.

Mode of Technology Transfer

It is recommended that the results of this study be summarized in an Engineering Technical Note. An article on this work has been prepared for the Facility Technology Application Test (FTAT; now FEAP) Notebook.

2 ENERGY SAVINGS CALCULATIONS

Based on the assumptions that (1) stratification causes increased heat loss through the walls and ceiling and (2) the degree of stratification is a function of ceiling height, buildings with high ceilings will have the most stratification and the the most heat loss. Therefore, this effort focused on chapels, gymnasiums, warehouses, and theaters that have ceiling heights ranging from 15 ft to 40 ft.

No attempt was made to monitor energy consumption in the demonstration buildings, since the energy savings expected from the operation of ceiling fans was small when compared to a building's total energy use. Experience has shown that when monitoring building energy consumption, small energy savings are nearly impossible to extract from the normal variations that occur in consumption. Instead, energy heat loss equations and temperature measurements were used to calculate potential savings.

Industrial-grade fans were installed in 10 buildings: five at Fort Carson, CO (two gyms, a motor pool, a chapel, and a military clothing store) and five at Fort McClellan, AL (a chapel, a gym, a publications warehouse, and a commissary dry goods warehouse). The number of fans to be installed in a given building was found by dividing the total square footage by the coverage area of a single fan (provided by the manufacturer). The diameter of the fans depended on the ceiling height: 48 in. fans for ceilings less than 25 ft; 56 in. fans for ceilings over 25 ft.²

Air temperature gradients in a building were measured using an array of five Type-T (copper/constantan) thermocouples. One thermocouple was placed at the ceiling and one at the floor, and three were spaced evenly between the floor and ceiling. A sixth thermocouple measured the outdoor temperature. The thermocouples were scanned every 15 seconds using a Campbell Scientific CR10 Measurement and Control Module. Each scan contributed to a 15-minute running average. At the end of a 15-minute period the values were recorded and new running averages were started.

Temperatures were recorded over a 2-week period in early January 1988 at Fort McClellan and over 2 weeks in late January 1988 at Fort Carson. During 1 week at each site the fans were not used (stratified conditions); during the other week they were used (unstratified conditions). A wide variation of weather conditions was experienced at both installations during the two weeks of testing.

Building Descriptions

Tables 1 and 2 list the important construction features of the demonstration buildings. They also show the number and size of fans that were installed.

Estimated Building Heat Loss Values

Using as-built drawings, the construction details and heat transfer characteristics of these buildings have been analyzed. Heat loss values (Btus/hr) were estimated using the areas (A) of the various components and thermal conductance (U) values found in the

²The Intelligent Approach to Commercial/Industrial Ceiling Fans (Leading Edge, 1985).

Table 1

Building Descriptions, Fort Carson

Bldg. No.	Area sq ft	Roof	Walls	Ceiling Height	Heating System	Fans	General
Motor Pool							
633	3840	Flat, built-up	Concrete/concrete block; lots of windows; 7 overhead doors	17 ft	1 air handler, 4400 cubic feet per minute (CFM); 4 unit heaters, 2320 CFM each	2 fans, 10,000 CFM each; 15 ft from end walls	----
Gymnasiums (2)							
1856 & 2357	9156	Built-up, on steel deck	8-in concrete blocks, 1-in. mortar, 4-in. brick facing	33 ft	4 air handling units, on concrete pads supported by roof truss members	4 fans, 21,000 CFM each	The two bldgs are mirror images
Chapel							
1850	4692	4-in. redwood decking; roofing felt; exposed metal	Same as gyms	sloped: 13.5 min to 26.5 ft max	Constant volume system	6 fans, 10,000 CFM each	Built same time as gyms

Table 2

Building Descriptions, Fort McClellan

Bldg. No.	Area sq ft	Roof	Walls	Ceiling Height	Heating System	Fans	General
Chapel							
2293	4664	2-in. redwood planking; rigid insulation; built-up roof	8-in., 3-core blks; 2-in. air space; 4-in., 3-core blks	Pitch: 2 rise, 12 run; min height 20.75 ft	Constant volume system; distribution at windows 4 ft above floor	3 fans; 10,000 CFM each	----
Commissary Dry Goods Warehouse							
2041	15852	Steel deck; rigid insul.; vapor seal; built-up roof	2 ext. walls; 8-in. blks w/in-sulated cores; 4 in. of grout; 4-in. brick face	28 ft	7 unit heaters	Six 48-in. fans, 10,000 CFM each	Largest bldg in test
Theater							
2101	6324	Steel deck; rigid insul.; built-up gravel roof	10-in. blks; 2-in. airspace; 4-in. brick facing	17 ft to drop ceil. (7.5 ft between roof & ceiling)	Constant volume system; 6 diffusers at ceiling	4 fans, 10,000 CFM each	
Gymnasium							
1702	9626	Steel deck; built up roof R19 insul. on drop ceiling	Concrete block; stucco exterior;	28 ft (airspace above drop ceiling)	2 large, high velocity air handlers	4 fans, 21,000 CFM each	Very similar to Fort Carson gyms

ASHRAE Handbook 1981 Fundamentals³. Values for infiltration and floor heat transmission were calculated using models presented in the *ASHRAE Fundamentals* (infiltration: Equation 18, p 22.13 and Equation 7, p 25.9; floor: Equation 6, p 25.8). The estimated heat loss values (UxA) are summarized in Table 3.

Temperature Data

These estimated heat loss values are used with three key temperatures: ceiling, floor, and mean. A change in any of these temperatures affects the overall building heat transfer rate; a reduction will result in energy savings. These temperatures were measured to determine the extent of changes due to ceiling fan operation.

The data collected for each building over the 2-week period covered a wide range of outdoor conditions. At Fort McClellan the high for the period was 52 °F; the low was 22 °F (early January). At Fort Carson the 2-week high was 59 °F; the low was 10 °F. Preliminary data analysis indicated that the inside temperatures were affected by the outdoor temperature and direct comparison of an average of all stratified temperatures (fans off) and an average of all destratified temperatures (fans on) would be misleading because the degree of stratification depends on outside air temperature. It was necessary to organize the data into bins* based on outside temperature to get useful values for the changes in the key temperatures. Tables 4 and 5 (Fort Carson and Fort McClellan, respectively) list averages for ceiling, floor, ceiling-minus-floor, and mean temperatures in the stratified (s) and destratified (d) cases. The first column is the outdoor temperature bin. These tables show the effectiveness of ceiling fans for reducing stratification.

Table 3
Heat Loss (UA) Parameters for Demonstration Buildings

Building, #	Sq Ft	Loss in Btu/hr/°F				
		Wall	Window	Ceiling	Floor	Infilt.
Fort Carson						
Motor Pool, 633	3840	1636	1170	845	144	8400
Gymnasium, 1850	9156	5400	N/A	1390	173	2880
Gymnasium, 2357	9156	5400	N/A	1390	173	2880
Chapel, 1850	4692	2100	1050	435	166	1010
Fort McClellan						
Chapel, 2293	4664	1110	1730	380	212	1170
Warehouse, 2041	15862	1975	N/A	2460	182	4020
Theater, 2101	6324	1790	N/A	950	258	1170
Gymnasium, 1702	9626	1260	N/A	480	111	2985

³ASHRAE Handbook 1981 Fundamentals (American Society of Heating, Refrigeration, and Air-Conditioning Engineers, 1981).

*The bins here are 5-°F temperature ranges. Data in a bin corresponds to outside temperatures equal to or less than the bin value but greater than the next lowest bin value. For example, data for 35.0 °F, 32.5 °F, and 30.1 °F would fall in the 35 °F bin, but data for 30.0 °F would fall in the 30 °F bin. Data within a bin was averaged.

Table 4
Reduction in Key Temperatures (°F), Fort Carson

Outdoor Temp	Ceiling		Floor		Ceil-Flr		Mean	
	(s)*	(d)*	(s)	(d)	(s)	(d)	(s)	(d)
Gym, 2357								
35	78.69	71.49	67.39	65.42	11.30	6.06	73.37	68.33
30	78.92	72.10	66.63	65.64	12.30	6.47	73.01	68.86
25	82.03	69.01	67.58	63.90	14.45	5.10	75.19	66.34
20	73.71	66.36	64.89	62.00	8.82	4.36	69.45	64.11
Gym, 1856								
35	73.17	81.85	64.60	74.45	8.56	7.41	68.94	78.17
30	75.28	81.32	65.63	73.67	9.64	7.65	70.81	77.49
25	76.87	81.38	65.17	72.65	11.71	8.72	71.43	77.36
20	76.50	81.49	63.77	68.25	12.73	13.24	70.35	76.76
Motor Pool, 633								
45	75.24	72.51	64.54	60.17	10.69	12.36	69.01	65.63
40	76.33	73.75	64.57	58.84	11.76	14.92	69.50	65.29
35	80.24	73.52	61.05	57.78	19.20	15.74	69.71	65.22
30	79.40	74.41	62.09	58.59	17.31	15.83	70.12	66.14
Chapel, 1850								
35	76.46	78.23	74.04	73.19	2.42	5.02	75.40	75.38
30	75.45	75.32	73.27	72.52	2.18	2.80	74.59	73.98
25	74.98	73.82	73.38	71.46	1.61	2.36	74.45	72.82
20	74.92	72.83	73.29	70.93	1.63	1.92	74.59	72.10

*Note: s = stratified (fans off); d = destratified (fans on).

Fort McClellan's gym is not included in Table 5 because of a failure in the data acquisition equipment. Temperature measurements are not available for when the ceiling fans were on. Data is available for the stratified case (fans off), however.

Tables 4 and 5 should be used with caution: values are averages obtained over a limited period of time. More extensive data collection would be necessary to reduce the anomalies that occur in the data. For example, Fort Carson gym (building 1856) had a runaway heating system during the first week of testing (destratified case, ceiling fans on). Thus, the high values for ceiling, floor, and mean temperatures were caused by the malfunctioning control system, not by the ceiling fans. In another case, heat loss at the Fort Carson motor pool (building 633) is caused primarily by infiltration and occupant behavior (e.g., opening and closing doors). In this building the highest degree of stratification existed when the floor temperature was about 50 °F; this low temperature can only be explained by opened overhead doors.

Table 5
Reduction in Key Temperatures (°F), Fort McClellan

Outdoor Temp	Ceiling		Floor		Ceil-Flr		Mean	
	(s)*	(d)*	(s)	(d)	(s)	(d)	(s)	(d)
Theater, 2101								
35	71.73	69.89	66.83	66.23	4.90	3.66	70.49	68.85
30	71.35	69.31	66.37	65.33	4.98	3.98	70.14	68.22
25	70.46	68.31	65.45	64.11	5.01	4.21	69.27	67.22
Commissary Warehouse, 2041								
35	58.49	59.14	55.07	57.67	3.42	1.47	56.87	58.38
30	57.89	59.01	54.44	57.62	3.44	1.39	56.44	58.35
25	57.17	57.64	53.49	54.97	3.68	2.67	55.68	56.48
Chapel, 2293								
35	62.62	68.00	61.46	66.00	1.17	1.99	62.37	67.54
30	64.53	68.56	62.54	66.34	1.99	2.21	64.08	68.04
25	65.05	63.12	62.58	61.89	2.47	1.24	64.51	62.89

*Note: s = stratified (fans off); d = destratified (fans on).

Also, one would expect to see a reduction in mean, ceiling, and ceiling-minus-floor temperatures and no change in the floor temperature. However, for the Fort McClellan warehouse and chapel, the ceiling, floor, and mean temperatures all increased with only a slight change in the ceiling-minus-floor temperature. These increased temperatures cause increased heat loss (these two buildings show negative savings; see Table 6). The interaction between the ceiling fans and the heating control system is unknown and may account for these anomalies.

Regardless of anomalies such as these, the tables show that ceiling fans affect stratification. In most of the demonstration buildings the fans reduced the ceiling-to-floor temperature difference. The other key temperatures were also lowered, with the ceiling temperature generally changing more than the floor temperature.

Estimated Savings

The energy savings from using ceiling fans can be estimated by multiplying the appropriate heat loss parameters (Table 3) by the proper changes in key temperatures (calculated from Tables 4 and 5). The UA (heat transfer) value for the ceiling is multiplied by the change in ceiling temperature. The heat loss values for the walls, windows, and infiltration are summed and the total is multiplied by the change in mean temperature. The floor heat loss parameter is multiplied by the change in the floor

Table 6

Estimated Energy Savings From Ceiling Fan Operation

Outside Temp	ΔT			Loss in Btu/hr			Savings
	Ceiling	Floor	Wall&Infl	Ceiling	Floor	Wall&Infl	
Fort Carson Gym, 2357							Avg Savings = 60,766
35	7.20	1.97	5.04	10,008	341	41,731	52,080
30	6.82	0.99	4.15	9,480	171	34,362	44,013
25	13.03	3.68	8.85	18,112	637	73,278	92,026
20	7.36	2.89	5.34	10,230	500	44,215	54,946
Fort Carson Motor Pool, 633							Avg Savings = 49,137
45	2.73	4.38	3.37	2,307	631	37,764	40,702
40	2.57	5.73	4.21	2,172	825	47,177	50,174
35	6.72	3.27	4.48	5,678	471	50,203	56,352
30	4.99	3.51	3.98	4,217	505	44,600	49,322
Fort Carson Chapel, 1850							Avg Savings = 5,380
35	-1.77	0.84	0.03	(770)	139	125	(506)
30	0.13	0.75	0.61	57	125	2,538	2,719
25	1.16	1.91	1.64	505	317	6,822	7,644
20	2.10	2.36	2.49	914	392	10,358	11,664
Fort McClellan Theater, 2101							Avg Savings = 16,937
35	1.84	0.61	1.64	4,526	111	10,373	15,010
30	2.03	1.03	1.92	4,994	187	12,144	17,325
25	2.14	1.34	2.05	5,264	244	12,966	18,475
Fort McClellan Commissary Warehouse, 2041							Avg Savings = (10,360)
35	-0.65	-2.6	-1.51	(1,599)	(473)	(9,551)	(11,623)
30	-1.12	-3.17	-1.9	(2,755)	(577)	(12,018)	(15,350)
25	0.47	-1.47	-0.79	1,156	(268)	(4,997)	(4,108)
Fort McClellan Chapel, 2293							Avg Savings = (11,527)
35	-5.38	-4.55	-5.17	(2,044)	(965)	(20,732)	(23,741)
30	-4.03	-3.8	-3.96	(1,531)	(806)	(15,880)	(18,217)
25	1.93	0.69	1.62	733	146	6,496	7,376

temperature. The sum of these products represents the total change in the heat loss of the building and the savings associated with the use of ceiling fans:

$$\text{Savings} = \sum (U_j A_j \cdot \Delta T_j) \quad \text{Eq (1)}$$

where $U_j A_j$ is the overall heat transfer value in Btu/hr/°F for component, and T_j is the change in temperature in °F for component j .

Table 6 presents the estimated savings for each of the demonstration buildings. The first column is the outdoor temperature at which the ceiling, floor, and mean temperatures were averaged. The next three columns are the changes in the key temperatures. These values were multiplied by the heat transfer parameters in Table 3 to get the Btus saved per hour at that outdoor temperature.

These results are very sensitive to the estimated heat transfer parameters, which are weighting factors that determine the importance of changes in the key temperatures. For example, at the Fort Carson motor pool, infiltration dominates the heat loss for the entire building. Thus, a small change in the mean building temperature (the temperature associated with infiltration) is more effective in saving energy than a more significant change in ceiling or floor temperatures. Also, differences between the estimated heat transfer parameters and the true value can cause a substantial error in the amount of energy actually saved. Because it was impossible to control all variables affecting building heat transfer (especially occupant behavior), the results presented in Table 6 need to be viewed with caution.

Two of the six buildings represented in Table 6 have negative savings associated with the operation of ceiling fans. These buildings did not show any severe stratification conditions during the period when temperatures were measured. No energy savings were computed for Building 1856 at Fort Carson because of the previously discussed problem with the building heating system during the first week of the test.

Table 6 shows that the savings associated with ceiling fan operation increase as the outside temperature decreases. Thus, heating energy savings associated with outdoor temperatures greater than 35 °F can be assumed to be small, since savings below that temperature are already small compared to total consumption. Since the changes in the key temperatures are not known for temperatures greater than 35 °F, annual savings figures must be based on the known quantities. For Fort Carson, there are 1940 hours in an average year that the outside temperature is between 35 and 20 °F (the range for data in this test). There are an additional 299 hours when the outside temperature is colder than 20 °F, making a total of 2239 hours below 35 °F. Similarly, Fort McClellan experiences an annual average of 511 hours of outdoor temperatures between 35 and 25 °F (the measured range) and 33 hours when the temperature is below 25 °F; the total at Fort McClellan is 544 hours.⁴ The total number of hours below 35 °F is multiplied by the hourly savings (Btus/hr) to obtain an estimate of the average annual energy savings (Btus). Table 7 presents the results for buildings that showed positive energy savings.

⁴Engineering Weather Data, Army Technical Manual 5-785, NAVFAC P-89, Air Force Manual 88-29 (Departments of the Army, Air Force, and Navy, 1 July 1978).

Table 7
Annual Dollar Savings From Ceiling Fan Operation

	Hourly Savings Btu/Hr	Annual Savings MBtu	Costs	Net Savings
Fort McClellan Theater, 2101	16,937	9.21	\$ 7.20	\$ 48.06
Fort Carson Gym, 2357	60,766	136.05	29.52	786.78
Fort Carson Motor Pool, 633	49,137	110.01	14.76	645.30
Fort Carson Chapel, 1850	5,380	12.04	5.40	66.84

Table 7 also shows operating costs and net savings. The ceiling fans installed at Fort Carson and Fort McClellan use approximately 55 W of electrical energy when operating at normal speed. The annual operating costs were computed using Equation 2:

$$\text{Cost (\$)} = 55 \text{ W} \times \text{hours below } 35 \text{ }^\circ\text{F} \times \frac{\$0.06}{\text{kWh}} \times \frac{1\text{kW}}{1000\text{W}} \times \# \text{ of fans} \quad [\text{Eq 2}]$$

The net savings in Table 7 were calculated by multiplying the annual savings in MBtus by \$6.00/MBtu for natural gas, then subtracting the annual operating costs.

USA-CERL contracted for the installation of ceiling fans for Fort Carson and Fort McClellan. Forty-eight fans were installed at a total contract price of \$15,472, which included all material and labor. The average cost per installed fan was \$322.00. Thus for the best case, Fort Carson Motor Pool, the estimated savings show a simple payback of just under 2 years. (The Fort Carson gym, 2357, appears to have greater savings, but it has four fans.)

The amount of savings depends strongly on the degree of stratification, since the two buildings with the greatest stratification (Fort Carson gym, 2357, and motor pool) had the greatest savings. For the demonstration buildings, stratification was not a severe problem. The ceiling to floor temperature difference exceeded 10 °F only for the two buildings just mentioned. For the other buildings the difference was generally less than 5 °F. Tables 6 and 7 show that if severe stratification does not exist, savings will be small or nonexistent.

3 STRATIFICATION AND OUTDOOR AIR TEMPERATURE

The amount of energy that can be saved using ceiling fans is directly related to the magnitude of thermal stratification in the building. Thus, identifying parameters that influence stratification is critical in determining where ceiling fans can be most effective. No previous work is available that provides a model for predicting the amount of stratification as a function of outdoor air temperature and building characteristics. The temperature stratification measurements taken during the demonstration project were analyzed to determine a method for predicting stratification within buildings.

Data were used only from the three buildings that indicated a stratification condition (ceiling to floor temperature difference greater than 10 °F). These three were Fort Carson buildings 1856, 2357, and 633 (the two gyms and the motor pool). Regression analyses were performed on the entire data set for each building to establish the relationship between outdoor air temperature, building conditions, and thermal stratification.

In addition, stratification data was collected at the USA-CERL highbay for 18 consecutive days in December 1987. This 6750-sq ft warehouse is constructed of 8-in. concrete blocks, with a 2-in. airspace between these and a 4-in. brick facing. Above the 40-ft ceiling, the roof consists of a steel deck, insulation, and built-up gravel. This space is heated by a constant volume system, with a diffuser at the ceiling.

Temperature data were taken in the highbay with the same equipment and methods used in the demonstration buildings. All data were taken in stratified conditions. The outdoor air temperature (T_{out}), ceiling-minus-floor temperature (T_{cf}), and the mean indoor temperature (T_{in}) were averaged into 15-minute values. The difference between the mean indoor temperature and the outside air temperature ($T_{in} - T_{out}$) was computed for each 15-minute interval. Each interval constituted a data set.

A total of 1430 data sets from the highbay were organized into 2.5 degree temperature bins based on the difference $T_{in} - T_{out}$. Within each bin all T_{cf} and $T_{in} - T_{out}$ values were averaged. For example, if the temperature bin is 35 °F, the values would be averaged for all data sets where $32.5 \text{ °F} < (T_{in} - T_{out}) \leq 35 \text{ °F}$. The end result is a data table that contains the averaged T_{cf} differences and the averaged $T_{in} - T_{out}$ differences for a series of 2.5 degree temperature ranges. Table 8 shows the temperature bin data for the USA-CERL highbay.

Linear regression analysis was done using $T_{in} - T_{out}$ (column 2, Table 8) as the independent variable and T_{cf} (column 3, Table 8) as the dependent variable. Simple linear regression showed that a relationship exists, but $T_{in} - T_{out}$ accounts for only about 69 percent of the variation in the ceiling to floor temperatures. A graph of the bin data indicates that a curvilinear model would provide better regression results.

To use such a model, the $T_{in} - T_{out}$ values were squared for each temperature bin. In the regression, $T_{in} - T_{out}$ and $(T_{in} - T_{out})^2$ were the independent variables (x and x^2). T_{cf} again was the dependent variable. The regression results indicate a high correlation. Effectively, 92 percent of the variation in T_{cf} can be explained by the difference between the mean indoor and outside air temperatures. Figure 1 shows the relationship between $T_{in} - T_{out}$ and T_{cf} .

Table 8

USA-CERL Highbay Temperature Data

Range	Mean Indoor - Outside Air ($T_{in} - T_{out}$)	Ceiling - Floor (T_{cf})	# of Sets in Bin
60.00	58.82	11.89	15
57.50	56.27	11.57	8
55.00	53.60	10.38	27
52.50	51.17	6.20	74
50.00	48.78	5.61	39
47.50	46.16	5.25	49
45.00	43.56	3.93	60
42.50	40.98	3.02	72
40.00	38.77	3.04	116
37.50	36.25	2.53	113
35.00	33.79	2.72	138
32.50	31.13	2.46	128
30.00	28.90	3.07	129
27.50	26.35	3.12	92
25.00	23.79	2.42	70
22.50	21.27	2.48	99
20.00	18.63	2.41	65
17.50	16.34	1.86	71
15.00	14.05	1.92	58

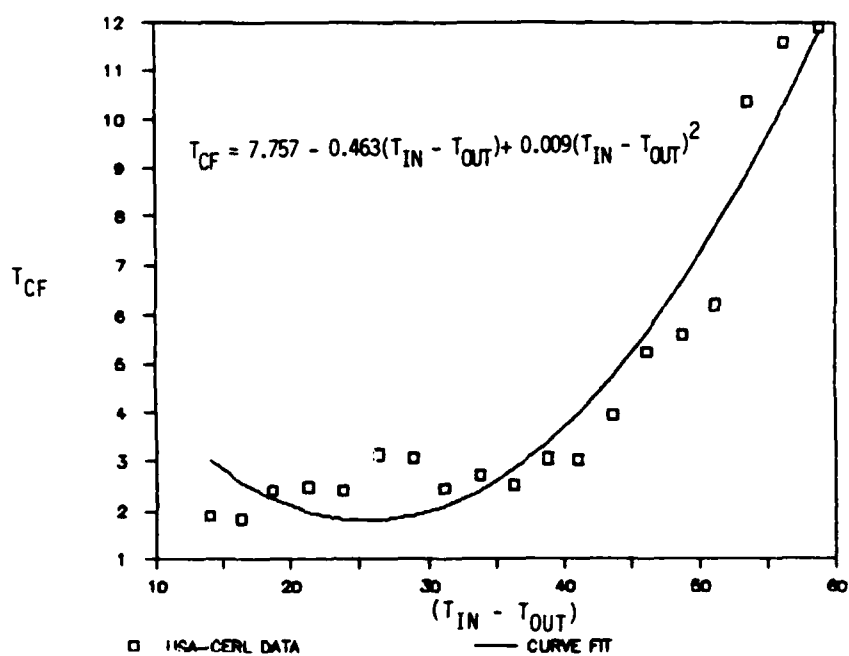


Figure 1. Result of regression analysis, USA-CERL highbay.

The same type of analysis was performed for the Fort Carson gyms and the motor pool. Unfortunately, the results did not parallel the findings from the USA-CERL high-bay: these results showed that the relationship between T_{cf} and $T_{in} - T_{out}$ is strongly linear. For Buildings 633, 2357, and 1856 (respectively), 89 percent, 86 percent, and 65 percent of the variation in ceiling to floor temperature differences can be explained by the $T_{in} - T_{out}$ values. Figures 2 through 4 show the results for the Fort Carson buildings.

The results indicate that the relationship between the degree of stratification and outside temperature can be readily defined for a specific building, given temperature data, but at this time it cannot be predicted in a general formula. Building characteristics such as infiltration and solar gains have an undetermined quantitative effect on this relationship. Additional work needs to be conducted on relating the degree of stratification to building characteristics, developing a more complex model, and gathering more extensive data to validate the model.

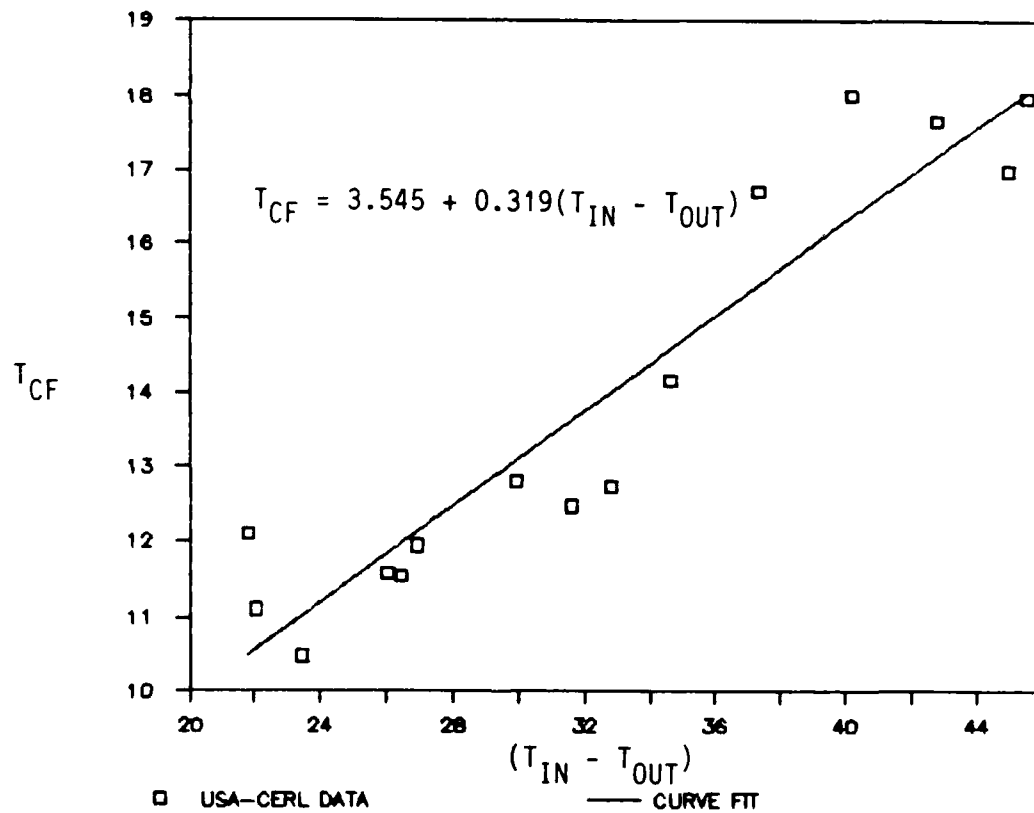


Figure 2. Result of regression analysis, Fort Carson motor pool, building 633.

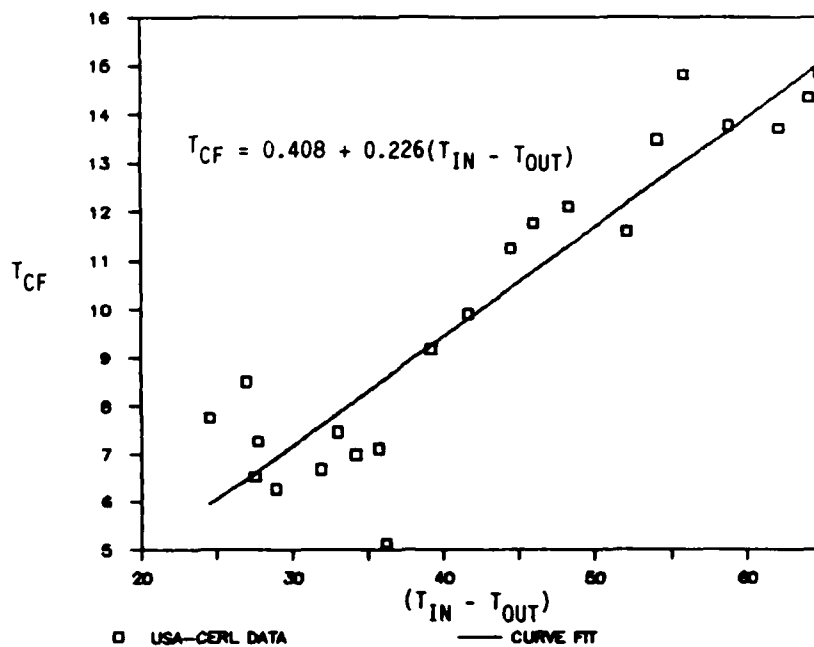


Figure 3. Results of regression analysis, Fort Carson gym, building 2357.

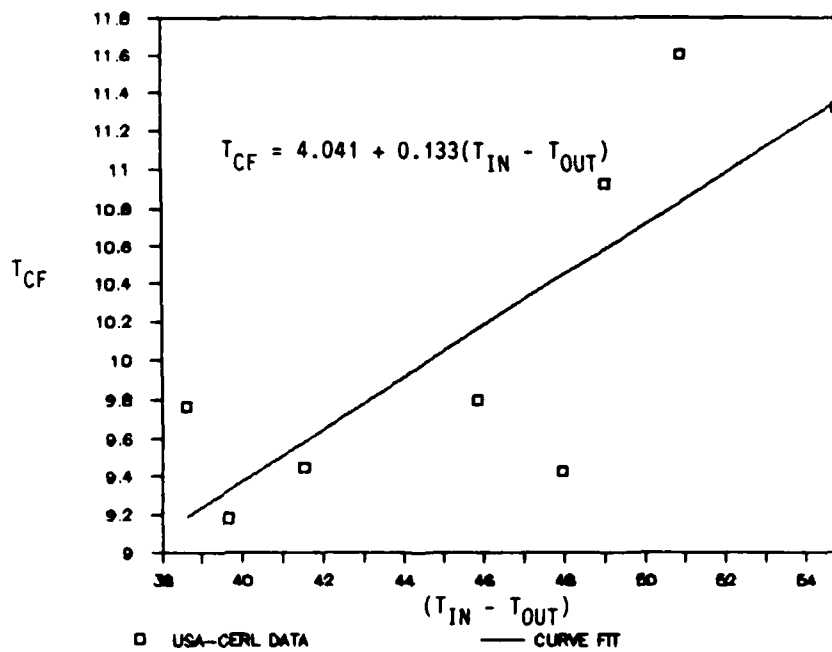


Figure 4. Results of regression analysis, Fort Carson gym, building 1856.

4 CONCLUSIONS AND RECOMMENDATIONS

Data collected at 10 Army buildings indicate that ceiling fans could possibly be used to save energy during the heating season. Because the initial cost of a ceiling fan is low, they may be cost effective even though the estimated savings for the demonstration buildings are small. Ceiling fans may become more economical when the degree of thermal stratification within a building increases. The demonstration buildings had relatively low amounts of thermal stratification.

As seen in Table 2, ceiling fans affect the stratification in buildings. The operation of ceiling fans during the heating season reduces the ceiling to floor temperature difference and in most cases reduces the mean temperature. However, these reductions do not always result in energy savings. Several of the buildings where data was collected showed an increase in the estimated hourly energy losses (Table 6). These buildings generally did not have a stratification problem. It is critical that the degree of stratification be evaluated before installing ceiling fans. If stratification is not a problem, then ceiling fans will not be effective in saving energy.

Thermal stratification in buildings is a complex process that depends strongly on the difference between the mean indoor temperature and the outdoor temperature. Thermal stratification is also affected by building characteristics, but the quantitative relationship is not known. More research is needed to define this relationship in a more complex model before general statements can be made about the effectiveness of ceiling fans in Army buildings.

However, certain qualitative conclusions about the characteristics which influence stratification can be formulated from the demonstration. In general, buildings that have forced air heating systems with supply ducts or unit heaters near the ceiling will have greater stratification than buildings with distribution systems near the floor. The buildings with the greatest amount of stratification (USA-CERL highbay, Fort Carson gyms and motor pool; see Tables 4, 5, and 8) have heating systems in which hot air enters the room near the ceiling. The chapels at Fort Carson and Fort McClellan have distribution system from around the floor level; these buildings do not show stratification problems.

Heating systems with low air supply velocity will increase stratification. The gymnasiums at Fort Carson have relatively low velocity air handlers, which are also located near the ceiling, and both buildings show stratification. In contrast, the gymnasium at Fort McClellan is very similar in construction to the Fort Carson gyms but has two air handlers with higher discharge rates; practically no stratification occurs there.

USA-CERL DISTRIBUTION

Chief of Engineers
ATTN: CEIM-SL (2)
ATTN: CECC-P
ATTN: CECW
ATTN: CECW-O
ATTN: CECW-P
ATTN: CECW-RR
ATTN: CEEC
ATTN: CEEC-C
ATTN: CEEC-E
ATTN: CERD
ATTN: CERD-C
ATTN: CERD-M
ATTN: CERM
ATTN: DAEN-ZCE
ATTN: DAEN-ZCI
ATTN: DAEN-ZCM
ATTN: DAEN-ZCZ

USAEHSC, ATTN: Library 22080
ATTN: DET III 79906
ATTN: CEHSC-FU 22060

US Army Engineer Districts
ATTN: Library (41)

US Army Engineer Divisions
ATTN: Library (13)

US Army Europe
AEAEN-ODCS/Engr (2) 09403
AEUES 09001
Allied Command Europe (ACE)
ATTN: ACSGEB/Engr
ATTN: SHIHG/Engr

8th USA, Korea (19)

ROK/US Combined Forces Command 96301
ATTN: EUSA-HHC-CFC/Engr

USA Japan (USARJ)
ATTN: DCSEN 96343
ATTN: Facilities Engineer 96343

Area Engineer, AEDC-Area Office
Arnold Air Force Station, TN 37389

416th Engineer Command 60623
ATTN: Facilities Engineer

US Military Academy 10966
ATTN: Facilities Engineer
ATTN: Dept of Geography &
Computer Science
ATTN: MAEN-A

AMMRC 02172
ATTN: DRXMR-WE
ATTN: DRXMR-AF

DLA ATTN: DLA-WI 22304

DNA ATTN: NADS 20305

FORSCOM
FORSCOM Engineer, ATTN: Spt Det.
ATTN: Facilities Engineer
Fort Carson 80913

HSC
Ft. Sam Houston AMC 78234
ATTN: HSLO-F
Walter Reed AMC 20307
ATTN: Facilities Engineer

INSCOM - Ch, Instl. Div.
ATTN: Facilities Engineer (5)

USA AMCCOM 61299
ATTN: AMSMC-RI
ATTN: AMSMC-IS

MTMC
ATTN: MT-LOF 20315
Oakland Army Base 94626
Bayonne MOT 07002
Sunny Point MOT 28461

NARADCOM, ATTN: DRDNA-F 01760

TARCOM, Fac. Div. 48090

TRADOC
HQ, TRADOC, ATTN: ATEN-DEH 23651
ATTN: DEH
Fort McClellan 36205

TSARCOM, ATTN: STSAS-F 63120

USACC
Fort Huachuca 85613
ATTN: Facilities Engineer (3)
Fort Ritchie 21719

WESTCOM
Fort Shafter 96856
ATTN: DEH
ATTN: APEN-A

SHAPE 09055
ATTN: Survivability Sect. CCB-OPS
ATTN: Infrastructure Branch, LANDA

HQ USEUCOM 09128
ATTN: ECJ 4/7-LOE

Fort Belvoir, VA 22060
ATTN: Canadian Liaison Officer
ATTN: British Liaison Officer
ATTN: Australian Liaison Officer
ATTN: French Liaison Officer
ATTN: German Liaison Officer
ATTN: Water Res Support Center
ATTN: Engr Studies Center
ATTN: Engr Topographic Lab
ATTN: ATZA-TE-SU
ATTN: STRBE-BLURE

CECRL, ATTN: Library 03755

WES, ATTN: Library 39180

HQ, XVIII Airborne Corps and
Ft. Bragg 28307
ATTN: AFZA-FE-EE

Chanute AFB, IL 61868
3345 CES/DE, Stop 27

Norton AFB CA 92409
ATTN: AFRCE-MX/DE

Tyndall AFB, FL 32403
AFESC/Engineering & Service Lab

NAVFAC
ATTN: Division Offices (11)
ATTN: Facilities Engr Cmd (9)
ATTN: Naval Public Works Ctr (9)
ATTN: Naval Civil Engr Lab (2)
ATTN: Naval Constr Battalion Ctr

NCEL 93043
ATTN: Library (Code L08A)

Engineering Societies Library
New York, NY 10017

National Guard Bureau 20310
Installation Division

US Government Printing Office 22304
Receiving Section/Depository (2)

US Army Env. Hygiene Agency
ATTN: HSHB-E 21010

National Bureau of Standards 20899

Defense Technical Info. Center 22314
ATTN: DDA (2)

199
1/89