CLIMATE INFLUENCE ON ATTIC RADIANT BARRIER ENERGY AND DEMAND SAVINGS

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Attic radiant barriers (ARB's) are increasingly promoted as a residential energy conservation measure. ARB's reduce radiant heat transfer between building roof and ceiling insulation, and must face an airspace for effective performance. They may be placed either directly atop the ceiling insulation or (preferably) near the roof underside to reduce degradation from dust, and to reduce radiant losses from attic ductwork.

With EPRI support, a detailed hourly building simulation with explicit radiant heat transfer algorithms was used to model ARB and non-ARB equipped homes in six U.S. cities. An ARB model used for previous studies was enhanced with dynamic convection coefficients and a detailed duct model, then calibrated with hourly temperature data from six Las Vegas homes monitored by Nevada Power Company.

Results project significant cooling demand and energy savings variations between the six cities. A simplified worksheet was developed from simulation results to promote rapid ARB savings estimates for varying ceiling R-value, duct location, and utility rates.

BACKGROUND

An attic radiant barrier (ARB) is a reflective foil surface placed adjacent an attic airspace to reduce radiative heat transfer. ARB's potentially benefit both building owners and electric utilities by reducing electrical energy use and demand during on-peak periods. Since 70-90% of summer ceiling heat gains normally occur via radiation from solar-heated roof surfaces [1], ARB's can significantly reduce summer day attic temperatures and ceiling heat gains. With an ARB, relatively weak downward convection becomes the primary summer attic heat transfer mode.

In a 1988 project for the Sacramento Municipal Utility District (SMUD) [2], Davis Energy Group (DEG) estimated ARB performance using a full-year hourly computer simulation program with discrete radiant and convective heat transfer algorithms, calibrated with test data available from Oak Ridge National Laboratory (ORNL) [3]. The calibrated model was then used to simulate ARB performance for typical ranges of Sacramento building thermal characteristics and ceiling insulation levels.

After the SMUD study, DEG simulated Miami ARB applications, and found notable differences vs. Sacramento results. While projected Sacramento ARB percentage annual energy savings were almost twice the demand savings, in Miami the projected energy and demand savings percentage were nearly equal. The differences appeared largely attributable to greater concurrence of solar and cooling loads in hot, dry climates (Sacramento) vs. humid climates (Miami). These results suggested that ARB utility value might vary significantly with climate, since demand savings are typically more valuable to utilities than energy savings.

This paper describes a project funded by the Electric Power Research Institute (EPRI), developed to evaluate ARB demand and energy variance with climate. Only "TRB" locations (at the roof underside), were considered in the project. TRB's are generally preferred over "HRB's" (placed horizontally on ceiling insulation) because they are less susceptible to performance degradation from dust accumulation, and their placement above ductwork will typically reduce summer duct gains and winter duct losses (assuming typical non-reflective duct surfaces). While most other ARB research activities have based their conclusions on testing in the Southeastern U.S., results presented here are based on calibration with Las Vegas field tests performed by the Nevada Power Company.

Nevada Power Field Study

The Nevada Power Company initiated a project in early 1988 to evaluate potential ARB benefits for new construction in Las Vegas. Three identical house pairs (two one-story, one two-story), with and without TRB's, were instrumented and monitored to record key temperatures and HVAC demand. The three non- radiant barrier (NRB) houses were separated by one block from the three TRB houses, and were identically oriented. Floor areas ranged from 1816 to 1976 ft^2; lower floors were slab-on-grade; walls were R11 and ceilings were R30. One unusual construction feature was the clay tile roof installed on plywood decking over an unventilated attic.

0.03 emittance (ASTM E-408) TRB foil was stapled atop the roof rafters prior to roof sheathing placement, with a relatively "snug" fit between sheathing and TRB (air space less than 0.25 inches).

The monitoring system included a remote recorder connected to four temperature transducers which monitored indoor air (at the thermostat), ceiling insulation (atop blown insulation layer), attic air (mid attic height), and roof underside. Weather data from the Nevada Power weather station (located five miles from the test site) included total horizontal insolation, ambient temperature, wind speed, and relative humidity.

METHODOLOGY

General

In this project, the ARB simulation model developed for the 1988 SMUD study was enhanced and calibrated using Nevada Power test data. The calibrated model was then applied to both NRB and TRB cases for three buildings in six U.S. cities: Las Vegas, Abilene, Knoxville, Miami, Minneapolis, and Portland, Oregon. (ETMY weather files were used for all cities except for Miami where a TMY file was available.) Parametric runs were completed for each building in each city with three ceiling insulation levels, with and without attic ductwork. Hourly weather conditions and heating/cooling loads from TRB simulations were input to an hourly HVAC system simulation program for calculation of energy and demand results based on loads, sizing, and operating conditions.

Enhanced Building Energy Simulation

For this project, one of the building energy analysis programs approved by the California Energy Commission (CEC) for residential "Title-24" compliance certification was enhanced by adding radiant transfer and duct models previously added for the SMUD study. (The duct model was developed for CEC Title-24 standards to simulate duct leakage and conduction losses, as a function of HVAC operating time, supply air, outdoor and attic temperatures, and duct insulation levels.) In addition, the model was improved by incorporating "dynamic" convection algorithms (based on flat plate heat transfer research by McAdams [4]) for hourly variation of surface heat transfer coefficients with heat flow direction, temperature differential, and surface tilt. The model used in the 1988 SMUD study [2] utilized fixed convective coefficients based on calibration with ORNL test data [3].

Model Calibration

The extensive Nevada Power data set was reviewed to identify three appropriate days for calibration studies. A peak summer day (high 111 °F, low 92 °F) and typical summer (high 101°F, low 75°F) and winter (high 55°F, low 34°F) days were selected. Selections were based on uniformity of starting and ending outdoor temperatures in addition to overall temperature ranges.

Attic air temperature was chosen as the calibration variable, since roof underside and insulation top temperatures appeared to be more variable with sensor placement. HVAC demand data were not used for calibration due to lack of uniformity in house occupancy patterns and thermostat control. Simulations were performed for all three calibration days, and simulated attic temperatures were compared to measured values. The Chi-square test, which sums squared differences, was used to evaluate "quality of fit" between distributions of expected and observed values. Chi-square values for each day/house combination were assigned weighting factors of 0.5 for the summer typical day, 0.3 for the summer peak day, and 0.2 for the winter typical day. These weighting factors were arbitrarily chosen to represent estimated importance of each "day type" on annual ARB value.

To calibrate the model, attic convection coefficients, attic infiltration parameters, duct leakage characteristics, roof absorptivity and infrared emissivity, and ceiling insulation U- value were varied within reasonable ranges to minimize Chi-square sums. Estimated attic moisture flux was not modeled.

Parametric Simulations

Parametric simulations were completed with the calibrated model to project TRB energy and demand impacts in the six locations for homes with asphalt shingle roofs over ventilated attics.

A 1540 ft^2 one-story house previously analyzed in ORNL ARB evaluations was used to evaluate performance for two house orientations. The first ("Building 1") assumed a south-facing orientation (as modeled by ORNL) with roof surfaces facing north/south; the otherwise identical Building 2 was assumed to face east with a corresponding east/west roof ridge line. Buildings 1 and 2 were selected to impose a cooling load range anticipated from the primarily "front and back" house glazing distribution, to assess house orientation impact on radiant barrier performance. House natural ventilation was modeled using standard California Energy Commission assumptions of vent area equal to 10% of total glazing area (18.5 ft^2), winter desired temperature of 78°F, and summer desired temperature of 68°F. (Venting is assumed to occur any time the house temperature is below the cooling setpoint and ambient air will reduce the indoor temperature to the desired temperature). Key house characteristics are shown in Table 1.

The building energy simulation generated full-year hourly load profiles for which the hourly HVAC simulation program developed energy use projections. Cooling systems were assumed adequately sized to satisfy peak hour cooling loads. With a smaller capacity cooling system, an ARB might not reduce peak demand since ARB cooling loads might still exceed system capacity (although indoor temperatures would be lower than with an identical NRB house).

Savings Worksheets

Project goals included development of one page location-specific worksheets to simplify application of project results to any residential building. The worksheet format was developed on a "per square foot of ceiling" basis to project TRB impact on both cooling and heating bills. Worksheets accommodate typical ranges for variables affecting TRB economics, including ceiling area and R-value, duct location, cooling efficiency, electric rates, and typical annual heating bills.

RESULTS

Calibration

Figure 1 compares average Las Vegas summer day (101°F maximum ambient) simulated and recorded temperatures for one house pair (NRB and TRB). Modeled summer day attic temperatures are slightly below recorded values at midday, and above recorded values during pre-sunrise hours; this relationship reverses in winter. Final calibration, while acceptable, might have been improved with an "on-roof" weather station and multiple attic temperature sensors. The Nevada Power weather

Table 1. Key Modeling Characteristics

Floor & Ceiling area, ft^2	1540
Wall Insulation	R-11
Floor Insulation	R-19
Glazing (% of ceiling area)	12%
Back glazing (% of total)	48%
Front glazing (% of total)	38%
Left glazing (% of total)	14%
Right glazing (% of total)	0%
Roof pitch	5 in 12
Roof absorptivity	0.9
Attic vent area, ft^2	1 per 150
Attic surface emissivity	0.9
TRB emissivity (bottom)	0.05
House infiltration	0.5 ACH
Daily internal gain	55.1 KBTU
Heating & Cooling setpoints	70/78°F
Cooling EER (95 °F)	8.0

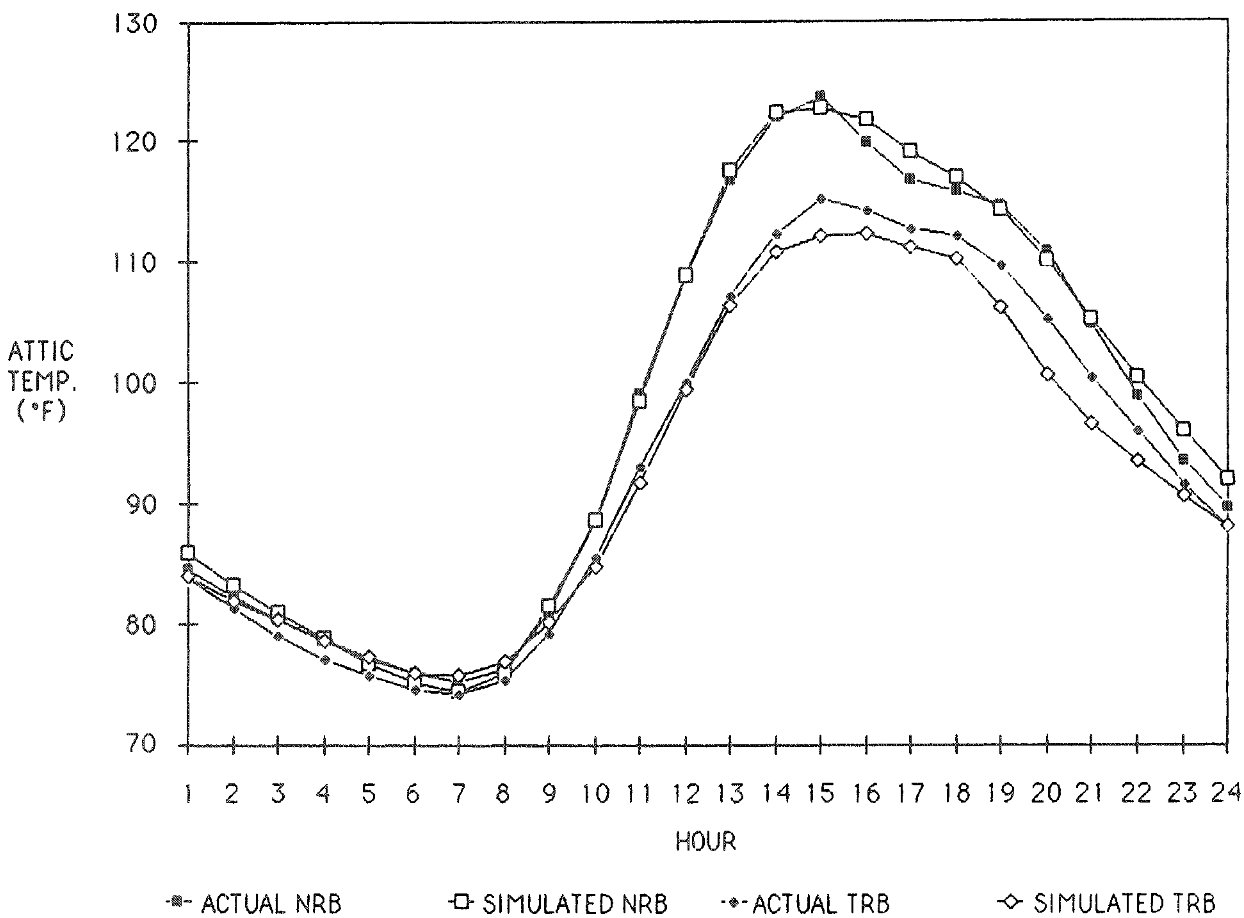

Figure 1. Las Vegas Attic Temperature Profiles

station, located approximately five miles distant above a large paved site (a possible summer "heat island"), may experience more extreme, time-delayed temperature patterns vs. the test site. Test house lawn sprinklers may lower local night air temperatures, helping explain lower recorded than modeled summer night attic temperatures.

Parametric Simulations

Cooling Energy. Table 2 presents TRB annual cooling energy savings "per ceiling ft^2" averaged for Buildings 1 and 2. As expected, greatest TRB cooling savings are projected in the warmest locations, for the lowest ceiling insulation levels, and with attic ductwork. Projected cooling energy savings show more than a tenfold range, from a low of .06 KWH/ ft^2-yr over R38 ceiling without attic ducts in Portland, to a high of 0.69 KWH/ft^2-yr over R11 ceiling with attic ducts in Las Vegas. For the lowest ceiling insulation cases, projected savings for Las Vegas and Miami are approximately four times greater than for Minneapolis and Portland. (The TRB performance range is somewhat extended by modeling R38 ceilings only in the latter two locations.)

Projected annual cooling energy savings depend largely on concurrence of solar gains and cooling loads. Annual cooling loads are typically 15 to 20% higher in Miami than in Las Vegas, but projected TRB savings are higher in Las Vegas because solar-driven daytime roof temperatures are higher. At the other end of the spectrum, projected TRB cooling savings are higher in Portland than in Minneapolis despite 100% higher annual cooling loads in Minneapolis. Again, greater concurrence of solar gains and cooling loads in Portland explains the result; muggy Minneapolis evenings require cooling when a TRB is of less value than during dry sunny afternoons.

Table 2 data shows projected TRB cooling season energy savings 18 to 30% higher when ducts are located in the attic. Projected TRB savings with attic ductwork are highest in the areas with highest solar loads and mean daily temperatures (Las Vegas and Abilene), where projected attic temperatures are also highest. Portland shows the least projected savings gain with attic ducts, due to mild temperatures and lower insolation.

Peak Demand. Table 3 summarizes potential peak demand savings for the six cities, based on "warmest day" cooling system energy use patterns. Data points show "Building 1 and 2 averages" of the peak for each case, rather than coincident NRB and TRB values. Projected demand savings range from a low of 0.13 Watts/ft^2 over R38 ceiling, without attic ducts in Minneapolis and Portland to a high of 0.58 Watts/ft^2 over R11 ceiling, with attic ducts in Las Vegas. The four-fold demand savings range is much lower than the ten-fold range in energy savings.

Improved TRB performance with attic ductwork is even more pronounced for demand savings than for energy savings. For the R19 case (the only common ceiling insulation to all locations), increased demand savings due to attic ducts range from 0.04 Watts/ft^2 in Minneapolis to 0.18 Watts/ft^2 in Las Vegas.

Figure 2 compares Abilene NRB and TRB projected peak day demand for both Buildings 1 and 2. During non-daylight hours the two Abilene buildings show identical projected demand patterns, with slightly higher demand for the more thermally resistive TRB attic cases. During solar hours, the projected Building 2 midday demand dip shows the east/west glazing impact compared to the relatively smooth demand patterns of (north/south glazed) Building 1.

Figure 2 shows how projected hourly TRB demand savings increase during morning hours and decrease after solar noon. This characteristic emphasizes the ARB role as an "anti-solar" technology, but also explains the major determinant of relative TRB demand savings among the six locations studied. When the NRB peak occurs nearer to solar noon, projected TRB demand savings are higher. For the selected Abilene day, the peak is relatively late (5 PM for NRB and 5-6 PM for TRB). By comparison, Knoxville's early September peak day has a narrower solar time window and demand peaks slightly nearer to solar noon. The Knoxville plots also show less difference between Building 1 and 2 demand patterns, and greater concurrence of NRB

Table 2. Projected Cooling Energy Savings (KWH/ft²-yr)

Location	R11 Ceiling Ducts: w/o	R11 Ceiling Ducts: with	R19 Ceiling Ducts: w/o	R19 Ceiling Ducts: with	R30 Ceiling Ducts: w/o	R30 Ceiling Ducts: with	R38 Ceiling Ducts: w/o	R38 Ceiling Ducts: with
Abilene	0.41	0.50	0.26	0.35	0.14	0.21	——	——
Knoxville	0.33	0.40	0.22	0.27	0.15	0.19	——	——
Las Vegas	0.57	0.69	0.37	0.49	0.25	0.32	——	——
Miami	0.55	0.67	0.37	0.45	0.25	0.32	——	——
Minneapolis	——	——	0.12	0.15	0.08	0.10	0.07	0.09
Portland	0.15	0.17	0.10	0.12	——	——	0.06	0.07

Table 3. Potential Demand Savings by Location (Watts/ft²)

Location	R11 Ceiling Ducts: w/o	R11 Ceiling Ducts: with	R19 Ceiling Ducts: w/o	R19 Ceiling Ducts: with	R30 Ceiling Ducts: w/o	R30 Ceiling Ducts: with	R38 Ceiling Ducts: w/o	R38 Ceiling Ducts: with
Abilene	0.33	0.46	0.19	0.31	0.14	0.21	——	——
Knoxville	0.37	0.48	0.25	0.34	0.17	0.24	——	——
Las Vegas	0.43	0.58	0.25	0.43	0.15	0.27	——	——
Miami	0.43	0.53	0.30	0.38	0.20	0.27	——	——
Minneapolis	——	——	0.21	0.25	0.15	0.20	0.13	0.17
Portland	0.33	0.42	0.22	0.29	——	——	0.13	0.18

and TRB peak demands. As a result, projected TRB demand savings are higher for Knoxville than Abilene.

Relative projected demand savings for the six locations appear to be substantially affected by the time of year when the peak day occurs. Complex effects of solar altitude angles on roof and glazing solar gains, and outdoor temperature patterns, influence TRB "demand savings".

Building Influences. Table 4 compares building 2 vs. 1 results by location for the R19 with attic ducts case. Results are presented to demonstrate orientation influences on both NRB performance and TRB savings. For NRB Building 2 (east/west orientation), projected cooling loads increase 8 to 33% relative to (north/south) Building 1, but highest percentage increases are for the two locations with low cooling loads due to sensitivity to increases in solar gains. House orientation has the smallest impact in Miami, where solar gains contribute a lower fraction of daily cooling loads than in the other locations. NRB Building 2 projected cooling demands increase less than projected cooling energy increases.

Building 2, with higher cooling loads per ceiling ft², shows higher projected TRB cooling energy savings and lower projected cooling demand savings than Building 1. The higher projected TRB energy savings are a result of additional cooling load during solar periods when the TRB is effective; lower projected demand savings probably result from peak loads occurring later in the day, when reduced insolation limits available TRB savings.

Attic Radiant Barrier Worksheet

The TRB worksheets summarize project results in a form designed to facilitate utility personnel and/or homeowner assessment of TRB annual energy cost savings for individual homes.

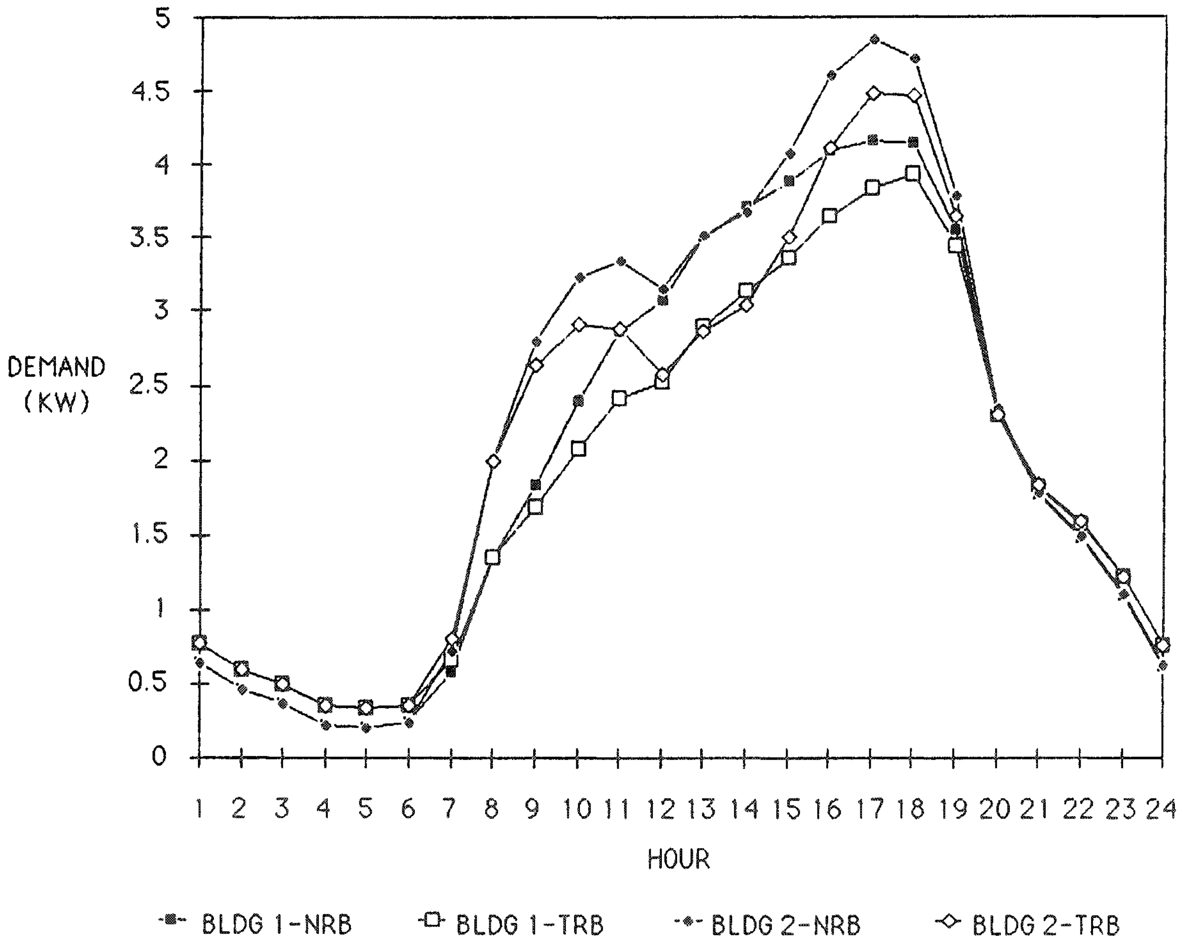

Figure 2. Abilene Building 1 and 2 Cooling Demand Profiles

Table 4. Cooling Performance Sensitivity Due to Orientation: Building 2 vs. Building 1

	Non Radiant Barrier		Truss Radiant Barrier	
Location	Total Energy	Total Demand	Energy Savings	Demand Savings
Abilene	+15%	+15%	+ 5%	+21%
Knoxville	+17%	+16%	+ 5%	+22%
Las Vegas	+18%	+10%	+ 2%	-30%
Miami	+ 8%	+ 2%	0%	- 7%
Minneapolis	+23%	+ 9%	+ 7%	-43%
Portland	+33%	+25%	+23%	+17%

Figure 3 is a completed worksheet for a sample two-story, 1800 ft^2 house with 1200 ft^2, R30 ceiling and R2.1 attic ductwork in Abilene, Texas. Other than ceiling and duct parameters, the only necessary inputs (and sample values) are: air conditioner efficiency (EER = 9.0), average summer electric rate ($.07/KWH), and average annual heating bill ($180).

"C" and "H" factors are selected from Table W1, and the cooling efficiency adjustment value (0.9) is selected from Table W2. The worksheet calculation projects $23 annual savings ($16 cooling, $7 heating) for the Abilene sample TRB application.

CONCLUSIONS

Simulations using a calibrated attic radiant barrier (ARB) model confirm "under-roof" (TRB) attic radiant barrier potential as an energy conservation and electrical load management technology. TRB's are projected to reduce seasonal residential cooling and, to a lesser extent (and therefore not reported in detail in this paper), heating loads, in all six locations studied in the project. Projected TRB savings occur from 10 AM to 6 PM, concurrent with summer utility peak loads. Where 24 hour cooling loads are experienced, TRB's are projected to reduce daytime energy use and slightly increase energy use at night.

Specific conclusions of this study are:

1. *TRB impact will vary significantly with climate; TRB's should be increasingly effective in reducing cooling energy use as insolation increases and ceiling R-value decreases.* Without attic duct work, projected annual cooling energy savings per ceiling ft^2, for single family homes with R19 ceiling insulation, range from 0.10 KWH/yr in Portland to 0.37 KWH/yr in Las Vegas and Miami.
2. *TRB's should benefit electric utilities by reducing summer on-peak energy use and demand, and by slightly increasing off-peak energy use in warm climates.* Without attic ductwork, projected peak day demand reductions for single family homes with R19 ceiling insulation range from 0.19 watts in Abilene to 0.30 watts in Miami, per ceiling ft^2. To insure demand savings, utilities could require cooling system downsizing with ARB's.
3. *TRB's over non-reflective attic ductwork should substantially increase TRB savings (in cooling and heating energy, and cooling demand), in all six locations studied, compared to non-attic duct cases.* Average TRB cooling energy savings for the six cities increase 27% for single family homes with attic ductwork over R19 ceiling insulation compared to non-duct cases.
4. *TRB's should increase average cooling system efficiencies.* By reducing daytime cooling loads and slightly shifting loads to non-solar hours, ARB's can lower average system condensing temperatures. Efficiency improvements will be greatest in desert climates with high daily temperature ranges.
5. *Building characteristics affect projected TRB cooling energy and demand savings.* Buildings with a majority of glazing oriented east/west are projected to experience increased cooling energy savings, decreased cooling demand savings, and decreased heating energy savings over identical houses with glazing oriented north/south.

ACKNOWLEDGMENT

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REFERENCES

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3. Oak Ridge National Laboratory. 1987. "Cooling Energy Measurements of Single-Family Houses with Attics Containing Radiant Barriers in Combination with R-11 and R-30 Ceiling Insulation." Oak Ridge, Tennessee.
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Location: Abilene, TX Owner: ____________

A. INPUTS

1. Ceiling area under attic (ft^2): A = 1200
2. Average summer electric rate ($/KWH): R = 0.07
3. Cooling system efficiency (EER): EER = 9.0
   (typically EER=SEER-1)
4. Estimated annual heating cost ($/year): W = $180

B. FACTORS & ADJUSTMENTS

Table W1: Savings Table (H and C)

		ATTIC DUCTS Cooling (C)	ATTIC DUCTS Heating (H)	NO ATTIC DUCTS Cooling (C)	NO ATTIC DUCTS Heating (H)
CEILING INSULATION R-VALUE	R-11	0.50	0.100	0.41	0.085
	R-19	0.35	0.066	0.26	0.060
	R-30	0.21	0.042	0.14	0.032

Table W2: Efficiency Adjustment Factor
(determine E from Table 2, based on EER on line 3)

	low efficiency		mid efficiency		high efficiency	
EER	6	7	8	9	10	12
E	1.29	1.13	1.00	0.90	0.82	0.69

C. PROJECTED SAVINGS CALCULATION

(1200 x 0.07 x 0.21 x 0.9) + (180 x 0.042) = $23

A	R	C	E	W	H	annual $
line 1	line 2	Table 1	Table 2	line 4	Table 1	savings
1200	0.07	0.21	0.9	180	0.042	$23

Notes:
1. For ceiling insulation R-values different from those listed, estimate "C" and "H" based on listed values.
2. Table savings values assume typical thermostat settings and residential use patterns. Actual ARB energy impact may vary substantially from worksheet projections.

Figure 3. Attic Radiant Barrier Savings Projection Worksheet