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A controlled field-test of radon reduction through solar ventilation at six homes in northeast Iowa: Proceedings of the International Radon Symposium, Nashville, TN 1995

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A CONTROLLED FIELD TEST OF RADON REDUCTION THROUGH SOLAR VENTILATION AT SIX HOMES IN NORTHEAST IOWA*

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ABSTRACT

This study evaluates an original radon mitigation technique which uses solar-heated ventilation air to reduce radon and other indoor air pollutants. Providing energy-efficient make-up air for combustion appliances and stack effect losses, the Solar Radon Reduction System (SRRS) improves indoor air quality through dilution, slight pressurization, and reduced radon infiltration. Solar heating of intake air produces net energy gain in cold seasons, and the SRRS blower provides summertime cooling during low outdoor temperatures. Research methodology includes synchronized hourly radon data collected at five test homes and a "control" maintained under closed conditions over five 10-day test periods. The control closely correlated weather-related radon trends, particularly with leaky homes, and thus serves as an appropriate reference for simultaneous multi-home remediation measurement. Installed at six homes in northeast Iowa, the SRRS was found to significantly reduce winter-time radon at all homes with elevated levels by an average of 49%.

INTRODUCTION

Greater awareness about carbon monoxide poisoning and radon lung cancer risks, as well as heavier use of building materials emitting harmful gases and more airtight buildings, has increased public demand for improved indoor air quality (IAQ). The U.S. Environmental Protection Agency (EPA) now warns that low air exchange rates can concentrate contaminants that would otherwise escape through leaks and cracks. Many indoor environments, particularly energy-efficient homes and under-ventilated office buildings and schools, may be dangerously polluted by toxic chemicals and gases, leading to the "sick building syndrome" (Mattill 1993).

Most approaches to reducing radon do not address other indoor air pollutants, such as backdrafted combustion appliance flue gas and volatile organic compounds from furnishings, and may even increase their accumulation through depressurization and short-circuiting. Moreover, all commercially available radon mitigation systems, even those equipped with heat recovery devices, operate at a net energy loss, and installation requirements and operational costs are prohibitive for many residents. One-third of all energy now consumed nationwide is for space and water heating, with residential heating alone accounting for one-fifth; operating conventional mitigation systems in every U.S. home with elevated radon would require the equivalent of several new nuclear power plants (Craig 1988). Thus a desirable IAQ management technique would provide pressurization to reduce both radon infiltration and backdrafting, as well as supply ventilation air to dilute persistent radon and other indoor air pollutants present. In addition, such a system with low installation and operational costs, net energy gain, and flexible for structure size or pollution levels, would be ideal.

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The Solar Radon Reduction System (SRRS),[1] devised by R.J. Klein to combine energy efficiency with low-cost radon reduction and IAQ management, was first installed at two test homes in 1990-91. Drawing on established mitigation techniques of ventilation, air supply and pressurization, the SRRS provides solar-heated make-up air for combustion appliances and stack effect losses. Compared to the typical solar collector recirculation configuration, its once-through solar heating of outdoor air is thought to utilize solar energy more efficiently than reheating indoor air, because the rate of heat transfer is greater with colder intake air (Kutscher 1992). Together with the fan, wiring, and ductwork, SRRS construction costs were estimated to be $200, about 10% of comparable commercial mitigation systems. Evaluations of SRRS performance were undertaken following specified EPA protocols as both a field test and demonstration for local health departments and non-profit organizations that wish to renovate affordable housing for radon and energy-efficiency.

As reported by Klein and Olson (1993, 1994) and Rhoads et al. (1995), the SRRS was shown to achieve significant radon reductions at both of the first installations, of up to 70% and 79% from closed house levels of 8.8 and 20.9 pCi/L. Energy benefits were found to lower heating bills, and homeowners expressed satisfaction with improved general indoor comfort. SRRS effectiveness was directly related to the duration and volume of air delivered in an airtight home, but less correlation was evident at a leakier house. Several possible system configurations and operational modes were investigated, including a "solar/furnace-trigger mode" to activate the fan both when air is solar-heated above indoor comfort levels and when home heating demands required furnace operation; a timer-based schedule was developed to maintain radon concentrations below the EPA guideline. Direct basement discharge of SRRS outlet air was determined to be preferable to distribution into living areas, as it rendered under-heated air less noticeable to occupants and sustained the strongest mitigation. SRRS summertime effectiveness and competitiveness with forced sump pit venting were also clearly demonstrated, and energy costs and savings were calculated.

Improvements developed and successful results obtained during the first two years of research established the SRRS as a promising radon reduction technique, but additional evaluations determining its applicability at a range of houses were needed to more fully document the system's effectiveness. Additionally, data acquired sequentially expressed a monotonic trend and did not exclude the possibility of systemic errors such as baseline shifts or external temporal influences; methodology to account for influences of weather and external factors was desired.

MATERIALS & METHODS

Initial screening of several additional homes was conducted to determine radon levels and solar accessibility, and the SRRS was subsequently installed at four new sites following the steps outlined in the SRRS instruction guide (Klein 1993), with modifications such as locating fresh air inlets below heated air outlets for the advantage of natural convection. To optimize solar heating, collectors were located to receive the most possible sunlight during winter and the best shielding from wind losses;[2] they were mounted parallel to the houses' south-facing walls and flush when possible to maximize insulation and collection of radiation escaping from the house. Collectors installed at Byron and Sager were vertically suspended on poles between 4" × 4" posts and can be tilted upwards during periods without snow cover. Intakes near garages or other obvious air pollutant sources were avoided, and air filters were placed at inlets and outlets. Pre-manufactured flat-plate air collectors were obtained from previous users or vendor-

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[1] U.S. Patent 5,186,160, Enviromiser Co., 4028 North Ave., Waterloo, IA 50702. Research funded by the Recycling & Reuse Technology Transfer Center, University of Northern Iowa.

[2] While collectors are best mounted facing solar south (in the northern hemisphere), an orientation of a few degrees west can improve performance since atmospheric haze often reduces morning solar insolation available. Solar gain can also be maximized by tilting the collector surface to an angle equal to the latitude plus 15° from horizontal (55° in northeast Iowa), although vertical mounting can be greatly augment efficiency with a horizontal reflecting surface such as snow cover and excess summertime radiation is reduced (Anderson 1994).

donated.[3] Mechanical thermostats were replaced with electronic temperature sensors and connected to custom-designed control units to regulate temperature-based fan operation.

In all, a "control" and five test houses were evaluated under closed conditions and various SRRS operational modes with direct basement discharge to determine radon reduction effectiveness and energy benefits. Minneapolis Blower Door Tests were conducted at each site to characterize leakiness, and time constants of air exchange were calculated as the inverse of air changes per hour (ACH), hours per complete indoor-outdoor air exchange (H/AC). Additional house characteristics were inventoried as potentially significant influences on radon behavior and overall indoor air quality. Washington and Control were older-style houses with stone foundations; Byron and Vermont were 1940s-era homes with block wall foundations; and Lovejoy and Sager were of newer construction, also with block wall foundations. All had full basements (dimensions matching entire above-grade area) except Lovejoy, which had a dirt crawl space beneath a living room addition. While all basements were at least partially finished, none were currently used as living spaces. Vermont and Byron had heated basements with open vents, and Washington, Sager, and Lovejoy basements were partially heated through leaky supply ducts.

As previous SRRS research involved progressive mitigation steps and extended system operation to obtain below-EPA guideline radon levels, similar trials and evaluation were anticipated to determine optimal system design for additional dwellings. In order to simplify subsequent installations, newly available Radon Alarm[4] monitors which have the capability to activate fans based on radon levels were incorporated into the SRRS strategy. The device is a microprocessor-driven semiconductor alpha-particle detector which relies on passive air diffusion of sample air to the detection chamber; highly resistive photovoltaic cells track radon alpha-particle emission as voltage pulses.[5] The calibration accuracy of the six Radon Alarms used in this study was tested both before and after the research periods, and correction factors were calculated to compare results.

Electronic control units were developed to transmit radon and temperature information to the SRRS fan as well as to enable PC monitoring of fan operation, as shown in Fig. 1. In the winter temperature-trigger mode, the SRRS fan is activated when the solar panel sensor reaches a specified temperature, 20°C (68°F) for this study; a 3-minute timer-relay prevents excessive cycling. With summer cooling setting, air temperatures below the set point activate the fan. The radon-trigger mode activates the fan when the Radon Alarm reaches a programmable mitigation threshold, 3.0 pCi/L for most of the tests in this study. The combined temperature/radon mode triggers the fan when either temperature or radon reach their set points. Evaluations of the new SRRS operational modes were conducted at the five test homes and control during five 10-day periods December 1994 through February 1995 in an alternating sequence to prevent entire test bias by weather or other time-related factors. To determine if below-EPA guideline levels could be attained with less fan operation, Lovejoy and Vermont were also tested with the (basement) radon threshold altered to 6.0 pCi/L; Washington was additionally tested with its Radon Alarm moved to the first floor as a tighter control on living-space radon.

Radon data were collected at each site in accordance with EPA Radon Measurement Protocols, including: closed-house conditions maintained for at least 12 hours before and during the entire test; heating systems operated normally; and the radon reduction system operating at least 24 hours before and during the entire test period (U.S. EPA 1993). Occupants were notified of the importance of proper testing conditions with written instructions and careful explanation. Site visits to switch system settings and retrieve data were made every two weeks; 3-4 days of separation between test periods allowed time for radon levels to adjust to the new operational configurations.

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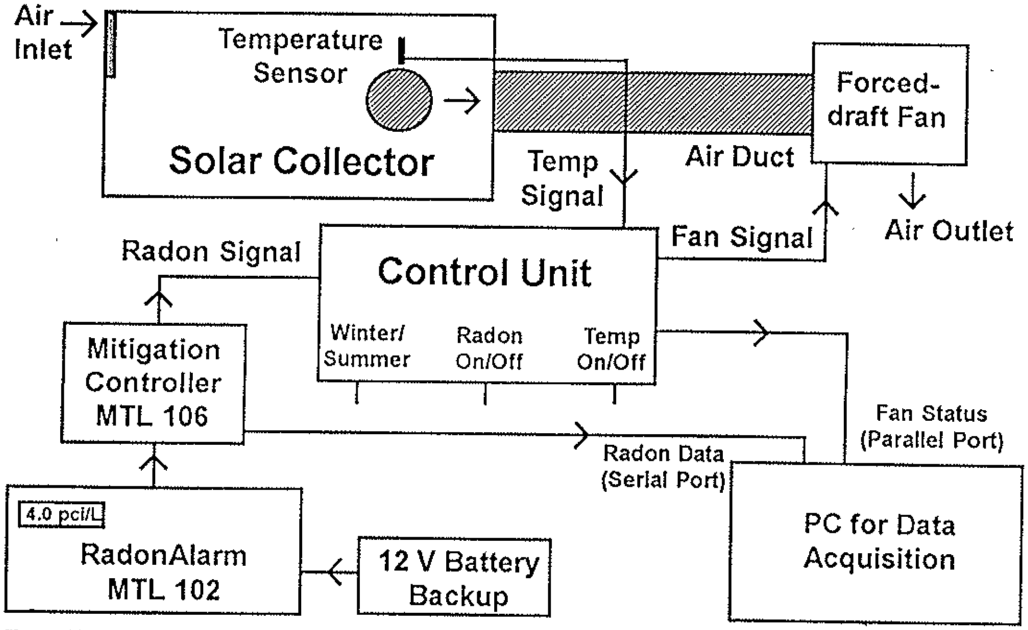
[3] GS Energy Industries, 108 Jefferson Ave., Des Moines, IA 50314.

[4] MTL-102, Monitor Technologies Ltd., 5800 Owensmouth #51, Woodland Hills, CA 91367.

[5] Pulses specific to alpha particles in width, height and intensity are summed 10 times over 82-minute intervals; 20 radiation-induced pulses are counted as 1 pCi/L with the assumption that the pulse rate is directly proportional to the surrounding radon concentration.

Numerous parameters were monitored with computer-controlled data acquisition systems[6] including inlet, outlet and basement temperatures, humidity, outdoor/basement pressure differentials, radiation striking the horizontal solar collector surface, and outlet air flow (see Rhoads 1995). Directed by custom software, radon levels and fan status were recorded at hourly intervals, and SRRS operation was additionally logged each time the fan turned on or off. Additional data collected consisted of upstairs radon levels, measured with continuous radon monitors[7] at Lovejoy and Sager and with mail-in activated charcoal samplers[8] at the remaining houses.



Temp-Trigger Mode: Fan comes on when temperature sensor reaches variable set point (winter = above 20°C, summer = below 20°C); stays on for at least 3 minutes every run

Radon-Trigger Mode: Fan comes on when radon reaches programmable level (3.0 pCi/L)
Temp/Radon-Trigger Mode: Fan comes on when radon and/or temperature reach set points

Fig. 1. SRRS and data acquisition system block diagram

Kruskal-Wallis one-way analysis of variance on ranks (ANOVA) and Dunn's method pairwise multiple comparison procedures were conducted for each house to determine significant differences between test modes. Time-weighted test period means were also corrected for monitor calibration and normalized to each house's closed house radon level to determine temporal effects. Heat gain resulting from solar panel operation was determined based on the temperature difference between outdoor ambient air and SRRS discharge air introduced indoors ($T_{inlet} - T_{outlet}$). Thus the experimental design enabled appropriate quantification of radon reduction and heat gain to evaluate SRRS performance in various operational modes at several test homes and to examine the balance of energy benefits and radon mitigation needs for each house.

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[6] 21X Micrologger, Campbell Scientific Inc., 815 W. 1800 N., Logan, UT 84321-1784; RD-Temp Logger, Differential Pressure Transducer PX-163-2.5, and copper/constantan thermocouples, Omega Engineering Inc., 1 Omega Dr., Box 4047, Stamford, CT 06907.

[7] Honeywell Radon Monitor 05-418, Nuclear Associates Div. of Victoreen Inc., 100 Voice Rd. Box 349, Carle Place, NY 11514-0349.

[8] Radon Test Kit, Air Chek Inc., Box 2000, Arden, NC 28704; Radon Detector, Enzone Inc., 4800 SW 51 St. #100, Davie, FL 33314.

RESULTS

Based on blower door testing, Lovejoy was found to be the tightest of the six houses studied, followed by Sager and Vermont, then Washington, Byron, and Control. Minimum levels of ventilation established by ASHRAE Standard 62-89 (15 CFM/person or 0.35 ACH) to maintain satisfactory indoor air quality are surpassed everywhere but Lovejoy with natural air exchange. Minneapolis Leakage Ratios indicate that sealing efforts would be quite effective at reducing infiltration at Control but only moderately so at Washington, Byron, Sager, and Vermont; additional weatherization efforts at Lovejoy would not likely be economical.

A complete set of charts containing blower door data and ventilation levels achieved; calibration and mailer results; real-time radon, temperature, fan and pressure data; statistical distributions of hourly radon levels; and time-weighted averages of additional parameters monitored are included in Rhoads (1995). Calculated house air time constants (H/AC) based on blower door natural infiltration estimates and measured SRRS air flow rates are shown in Fig. 2. Samples of real-time data collected at Lovejoy are shown in Figuress. 3-4. Basement radon data points represent a moving average of the preceding 22 hours, and first floor radon data are eight-hour averages. Fig. 5 summarizes radon results, adjusted with correction factors determined during post-research calibration testing for all six houses.

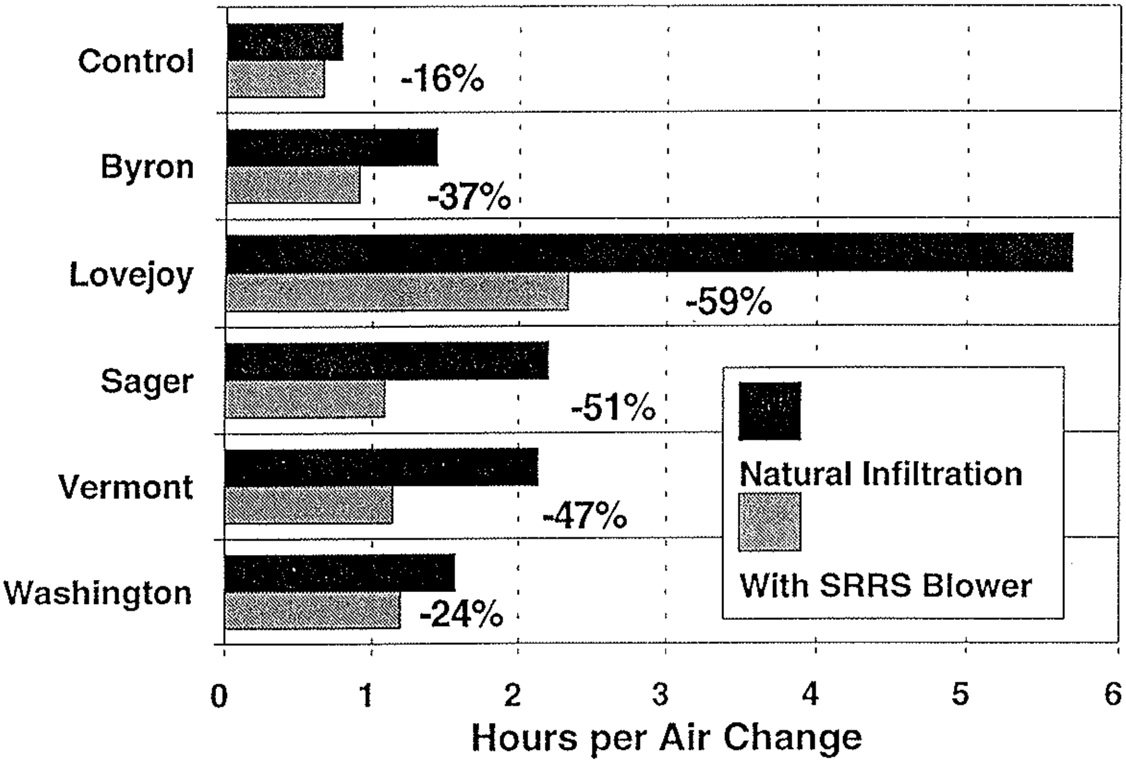

Fig. 2. Effect of SRRS operation on house air time constants based on blower door and air flow measurements

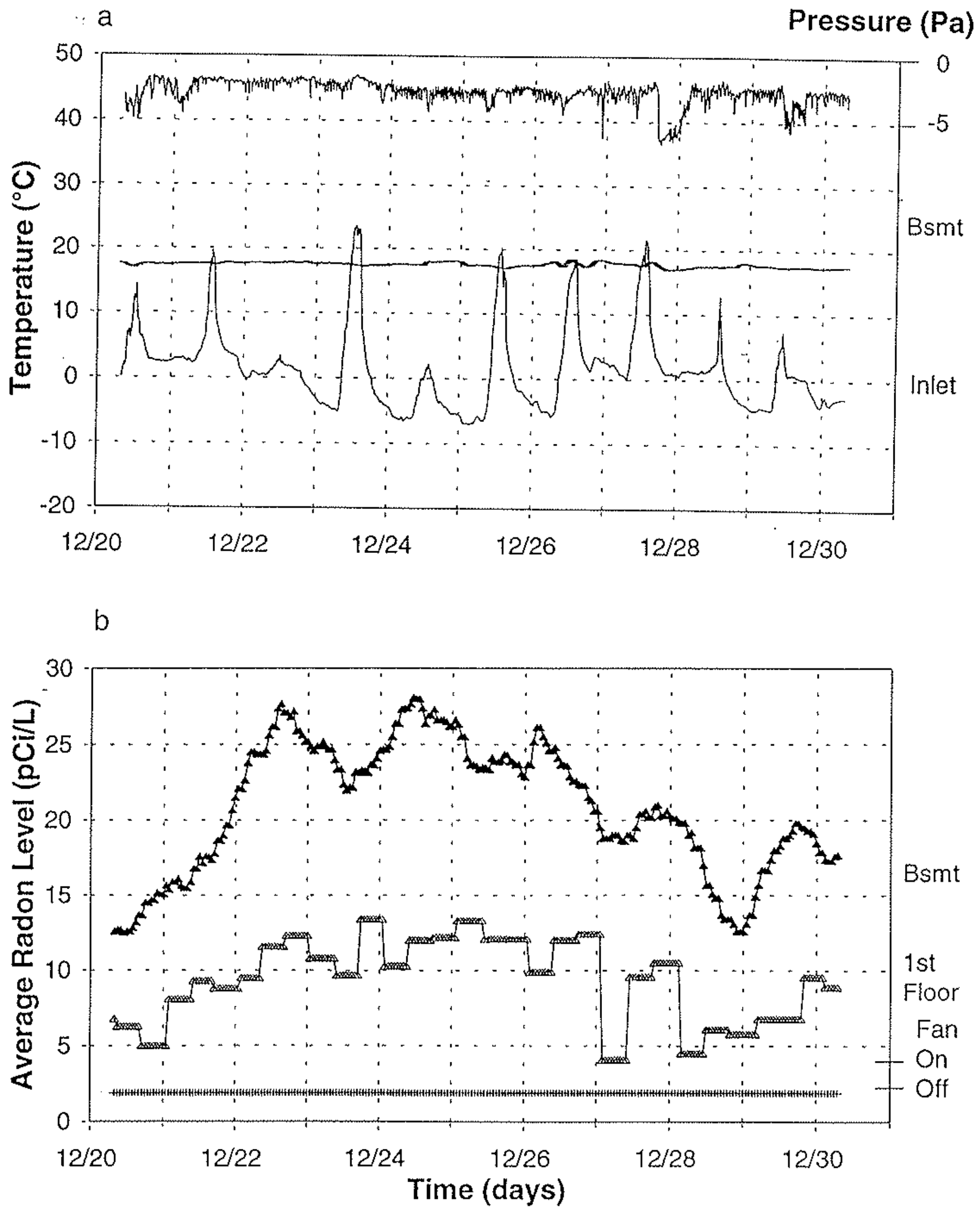

Fig. 3. Lovejoy under closed house conditions, period 2: (a) outdoor/basement pressure differential and fan outlet and inlet temperatures; (b) fan status and radon data

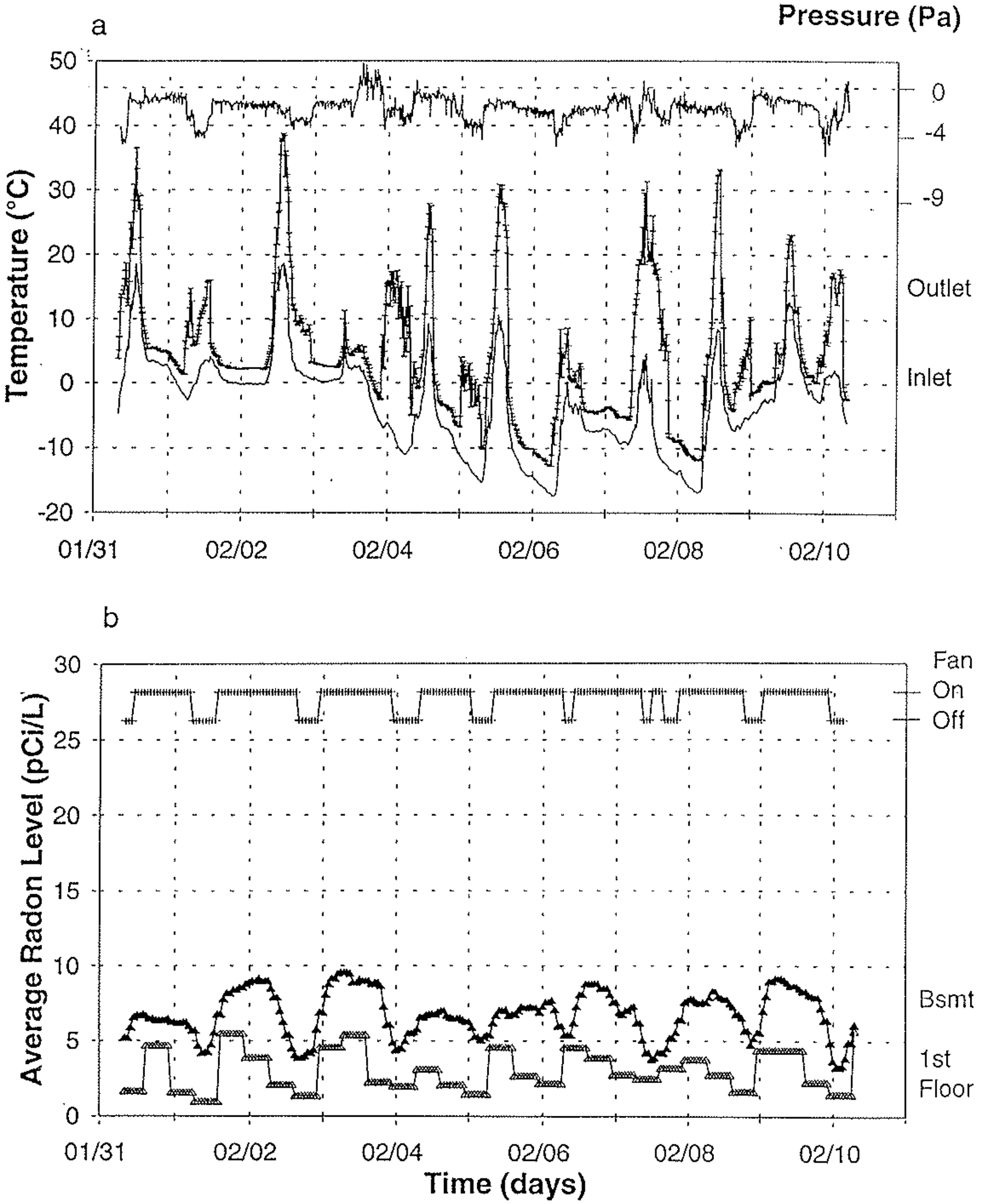

Fig. 4. Lovejoy with temperature/radon-trigger SRRS operation (6.0 pCi/L threshold), period 5: (a) outdoor/basement pressure differential and outlet and inlet temperatures; (b) fan status and radon data

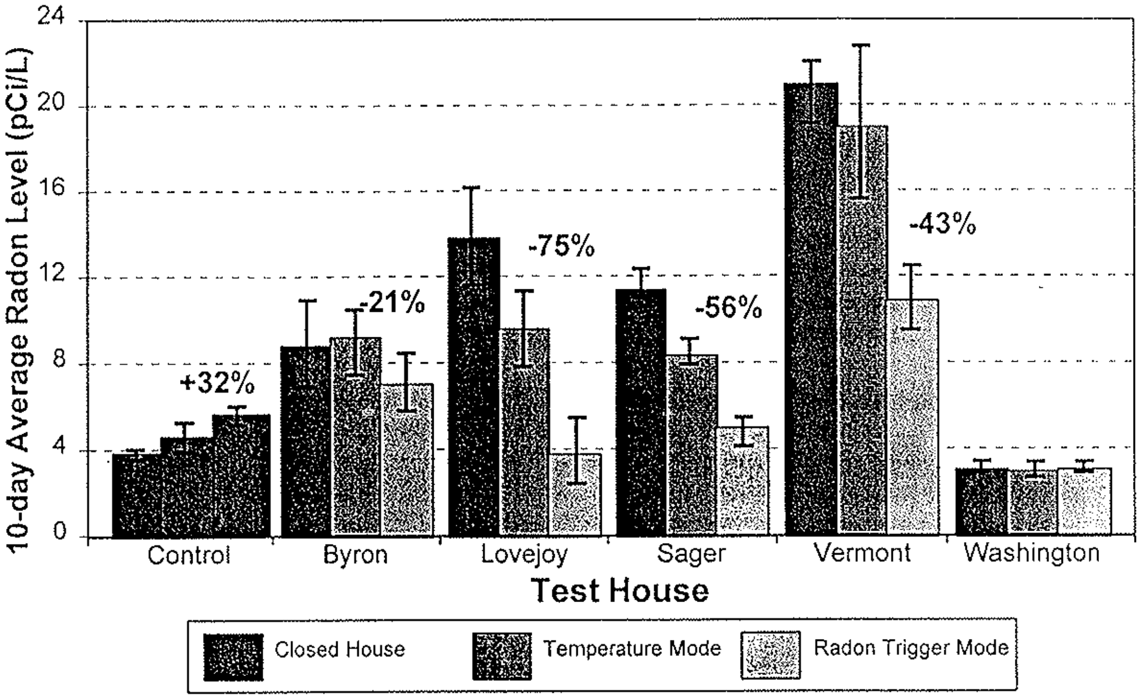

Fig. 5. SRRS basement radon reduction compared to closed house conditions; capped bars indicate 25th and 75th percentiles of real-time data

DISCUSSION

The six Radon Alarms used for this study were determined to be calibrated within ±0.2 pCi/L (standard deviation of monitor means) or 94% (standard deviation divided by group mean) during initial side-by-side operation. Post-research testing revealed some deterioration in calibration, particularly in the units used at Lovejoy and Washington; between July 1994 and March 1995 the standard deviation of monitor means increased to ±2.3 pCi/L, and calibration accuracy decreased to 81%. While Radon Alarm owner-users are advised to send in their units for recalibration only every 10 years, those intending to operate mitigation systems in a radon-trigger mode would benefit by periodically comparing readings to charcoal mailers and adjusting the mitigation threshold accordingly.

SRRS fan air flow varied from 62 CFM at Washington to 105 CFM at Sager, even though each had fans with manufacturer's ratings of 75 CFM. Washington's solar panel had air filters placed at both openings which likely reduced air flow; Sager also had filters which were newer and its delivery duct work was the shortest and had the fewest bends. These factors suggest that higher fan efficiency may be gained by cleaning filters and shortening and straightening ducts. Passive infiltration through the SRRS outlet during periods of non-operation as high as 20 CFM at Sager confirms that significant amounts of low-impedance make-up air are drawn in by combustion appliance- and stack effect-induced negative pressures. Variable wind loading on the building shell could also be a factor in both the forced-draft and passive measurements. The effect of SRRS operation in shortening the time a volume of air remains indoors is dependent upon fan efficiency, house leakiness, and envelope volume, as shown in Fig. 2. SRRS fans at the houses studied add between 0.20 ACH (Washington) and 0.47 ACH (Sager); the calculation is shown for Control even though no SRRS was installed there to demonstrate that the relative amount of air a 75 CFM fan adds to a very leaky house is much smaller.

House leakiness has the greatest affect on SRRS ability to improve house ventilation; as the tightest house, Lovejoy's SRRS shows the greatest proportional effect, yet it has the largest heated volume and has only moderate fan efficiency. Byron and Sager are similar sizes and have similar fan flow rates, but Byron is much leakier; Sager's SRRS shows a greater effect in increasing the air change rate. However, fan speed can also compensate for leakiness and size effects; Sager has higher natural infiltration and is larger than Vermont but has higher fan speed and thus a greater SRRS effect.

Test Period Data

Basement/outdoor pressure differential data at Lovejoy and Sager indicate that SRRS operation does indeed pressurize the basement relative to outdoors; its effect is seen most clearly at Lovejoy during test period 5 (Fig. 4) with negative pressures of -3 Pa abated to nearly 0 Pa in response to fan status. Test period means for both Lovejoy and Sager indicate that duration of fan operation affects long-term house pressures as well even at leaky houses.

Radon levels at Control exhibited peaks and valleys spanning 1-2 days with an overall increase during each succeeding test period, indicating a rising baseline due to common weather variations and other external factors which may well affect SRRS efficiencies calculated for the other homes studied. Since Control's Radon Alarm calibration appeared to shift toward lower radon readings during the test periods, this baseline rise may be even steeper than measured. Although Control was the leakiest house in the study with relatively low radon levels, it does appear to serve as a good indicator of external driving forces of radon infiltration for houses in the test area. The correlation of real-time radon trends at Control and a test house located 10 miles away is graphically illustrated in Fig. 6. A three-fold increase in radon occurred on Jan. 6 at Byron, closely coinciding with a large peak at Control and a local storm front, as evidenced by warmer inlet temperatures, decreased solar gain, and a drop in atmospheric pressure.

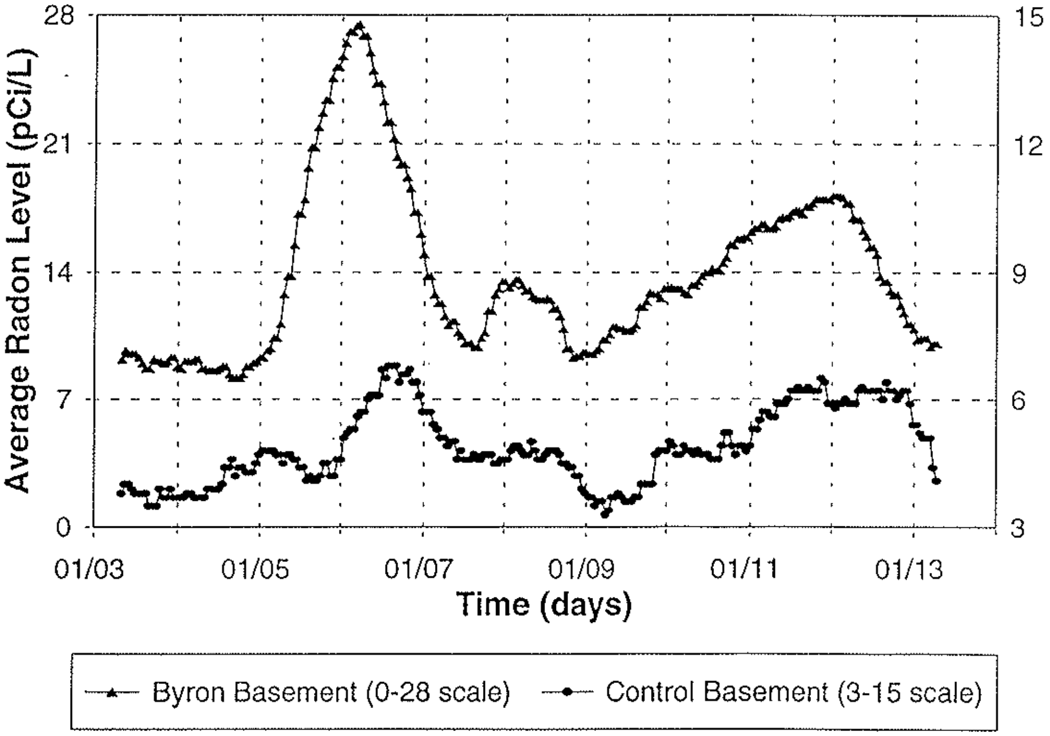

Fig. 6. Byron and Control period 3 radon data

Of all the SRRS test houses, Byron's radon level appears to be most affected by weather and external factors, as shown in Fig. 7. Byron was the only house which showed lower radon levels during closed house testing than with subsequent test modes, although its monitor calibration drift may have inflated results during the latter test periods. Washington also showed little response to SRRS operation throughout the study. Byron and Washington are the leakiest after Control, supporting the hypothesis that tighter houses respond better to increased basement ventilation. House leakiness was not found to be correlated to lower radon levels; since upper-story leaks contribute substantially to the stack effect and negative basement pressures, radon infiltration may be increased with higher air change rates.

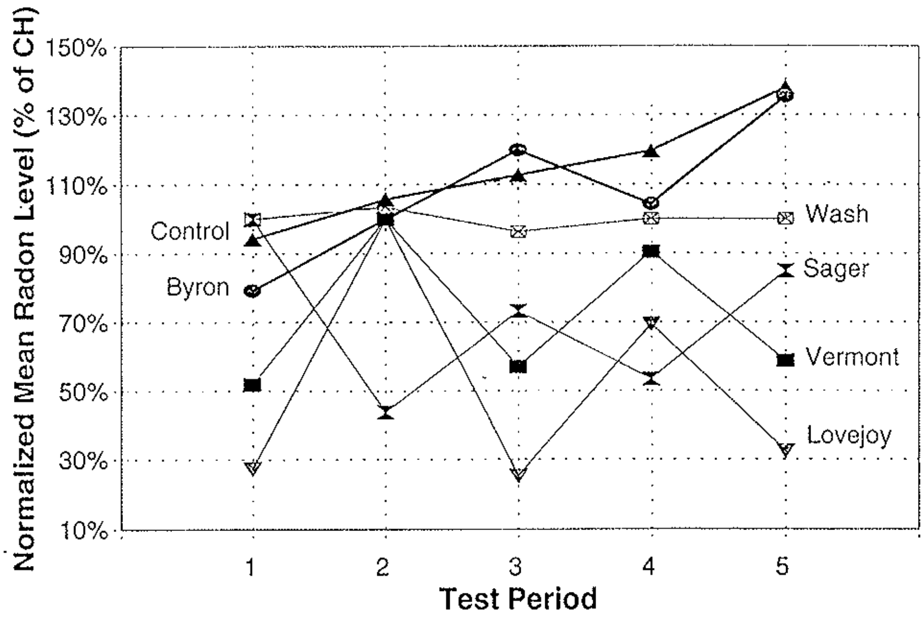

Fig. 7. Radon variation over research period; test period means corrected with monitor calibration factors and normalized to closed house mean for each house (CH = 100%)

The radon trends at Vermont and Lovejoy are similar to each other and opposite Sager, as these two groups were operated in alternating modes over the test periods (Fig. 7). Mean radon levels and duration of fan operation are correlated well at these three tighter houses, as shown in Fig. 8. The linear regression slope is steeper for Vermont and Lovejoy (-0.4 pCi/L per hour of fan operation) than for Sager (-0.2 pCi/L per hour), indicating a larger influence of external factors at Sager. Byron does show a slight correlation as test modes were repeated during periods of varied radon potential. As a large, leaky house with low fan efficiency and low winter-time radon levels even in closed house conditions, Washington's SRRS showed little effect on basement radon.

Energy Analysis

Outdoor temperatures experienced during the research period were near the seasonal average (32-50 heating degrees/day) for Iowa; they also appeared to be inversely correlated to solar insolation, with the coldest test periods also having the greatest amount of solar radiation available. This is presumably due to cloud cover holding in ground-level thermal radiation while blocking sunlight; temperatures well below freezing prevent vapor formation and thus the coldest winter days are generally cloudless. This indicates that once-through SRRS solar collectors may achieve higher efficiencies than may be apparent by seasonal climatic data as larger solar gains may occur on colder days.

While the largest overall temperature differentials were achieved during winter-temperature trigger SRRS operation, significant energy benefits over direct outdoor ventilation were seen in all modes. Outlet temperatures were always noticeably augmented over inlet temperatures, apparently due to both collection of solar insolation and the solar panel's ability to capture thermal radiation escaping from the building envelope. During periods of peak sunshine, discharge air was typically heated from outdoor temperatures of 0-5°C to outlet temperatures of 35-40°C, with gains of up to 55°C occurring at Byron and Washington. Although substantial amounts of cold air were introduced indoors during extended radon-trigger operation at most houses, no complaints were reported by homeowners. The discharge of air into the basement was theorized to mediate heat gains and losses, as the building foundation and surrounding earth provides thermal storage mass.

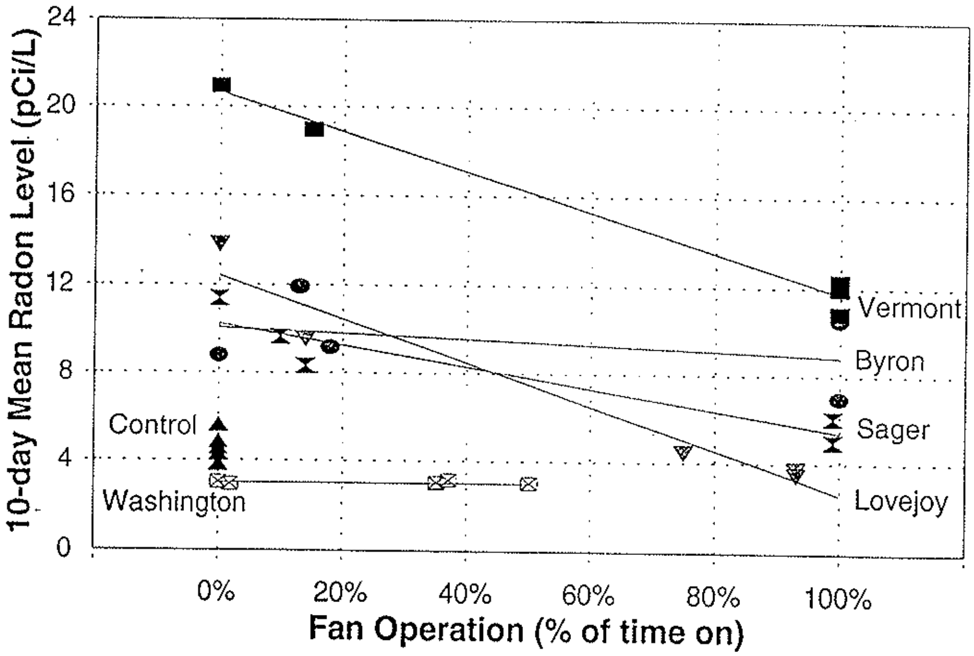

Fig. 8. Effect of SRRS operation on basement radon (corrected with monitor calibration factors); lines show linear regression for each house

CONCLUSIONS

The results presented in this study show that the Solar Radon Reduction System is effective in reducing indoor radon concentrations with energy savings. The SRRS was found to achieve significant radon reductions in all test houses with elevated levels; three of the five were maintained below 4 pCi/L during 10-day test periods. Radon was substantially reduced at all test houses even with temperature-based operation, which provides the largest energy gain. An inverse correlation of winter temperatures and solar availability was identified as beneficial to the SRRS approach since insolation is maximized when heating is needed most. Discharge air temperatures were always augmented over outdoor intake temperatures, aiding low-cost operation even with extended radon-trigger system configuration.

Due to the ventilation, air supply, and pressurization principles incorporated in SRRS operation, radon reduction efficiency was found to be related to the duration of system operation and dwelling airtightness; leaky houses were more affected by weather and other external factors throughout the research period. Basement pressurization was clearly related to fan operation in an airtight home and moderately so in a more leaky home. Improved weatherization, such as sealing cracks and other openings in the foundation to enhance the pressure barrier and insulating upper stories to reduce convection losses and stack effect forces, as well as higher fan capacity, will likely improve SRRS effectiveness.

The control house showed natural variability of indoor radon levels over the five test periods, with progressively increasing means toward the end of the study; its replication of radon trends at test sites established it as an appropriate indicator of external factors. The greatest mitigation was seen at Lovejoy, which employs no combustion appliances and had the only mitigation with sump pit sealing. Lovejoy's 10-day radon means were reduced by 73% in the basement and 68% on the first floor, from closed house levels of 13.8 and 6.2 pCi/L.[9] Below-EPA action levels were achieved on first floors at Byron (3.9 pCi/L), Lovejoy (3.0 pCi/L), and Washington (2.9 pCi/L); favorable first floor levels were also shown at Vermont (5.0 pCi/L) and Sager (5.6 pCi/L) from higher closed house levels during cold winter weather.

Implications of Findings

Controlled evaluation of varied radon mitigation techniques at specific sites is particularly hindered by the numerous factors that determine indoor radon concentrations, including the strength of the radioactive source, the gas entry rate, weather forces and house characteristics. Radon emanation is dependent on soil composition and condition, such as moisture content, temperature and porosity (Brambley and Gorfien 1986). Effects of construction factors, such as dwelling tightness and distribution of leaks, integrity of the basement slab and foundation walls, and characteristics of sumps, drains, pipe entry points, and crawl spaces, are unique to each house and often indeterminable before mitigation is attempted, since even well-ventilated homes may have high radon levels due to negative basement pressure.

Most homes and buildings are indeed affected by variable negative pressures caused by the stack effect forces, wind-driven pressure differences, and combustion appliance and exhaust fan operation. Natural infiltration rates can also vary seasonally due to changes in snow cover, frost level and soil moisture or even hourly based on barometric pressure, convection, and effects of wind direction and velocity (Fleischer 1988). Given the range of factors that affect radon levels in a dwelling, the number of radon mitigation options, and the fact that no single system can universally guarantee acceptable indoor radon levels, homeowners and radon mitigation contractors must weigh several variables when developing a mitigation approach. Installation and operating costs associated with each mitigation step often compound the selection and evaluation.

Through extensive monitoring of parameters and carefully-planned experimental design, this study has effectively demonstrated SRRS applicability to a range of houses, establishing the system as an attractive alternative to conventional mitigation. Compared to other radon mitigation options, the SRRS extends several advantages:

- radon reduction with net energy gain;
- flexible fan/panel sizing for larger structures or higher radon levels;
- reduced backdrafting potential, improvement in overall IAQ;
- user-controlled operation to balance energy demands and desired radon reduction;
- affordable, "do-it-yourself" installation;
- year-round energy savings and low operating costs;
- consists of used/recycled resources; and
- incorporates renewable energy into the radon industry.

These benefits suggest more homeowners and even commercial and manufacturing facilities may be likely to install radon mitigation systems, and be less likely to discontinue their operation. A market study conducted for the SRRS found that nearly two-thirds of northeast Iowa homeowners surveyed would prefer to install a radon mitigation

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[9] Radon levels corrected with calibration factors.

system themselves as opposed to a hiring professional contractor, indicating that a ready-made simple installation kit may best advance the SRRS radon mitigation strategy (Rhoads et al. 1995). Additionally, 77% of respondents indicated that tax credits would favorably influence their radon mitigation purchase decision; state or federal renewable energy incentives would certainly promote such investments. Energy gain afforded by the SRRS solar pre-heating approach can help offset increased heating loads demands as OSHA ventilation guidelines become more stringent in residential, educational and industrial settings.

Recommendations

The amount of solar insolation that can be utilized by the SRRS can be optimized by solar panel orientation, size, and capacity based on ventilation needs and a structure's geographical location (Reif 1981). Significant volumes of ventilation and make-up air are required to maintain IAQ and safe working environments in many commercial and manufacturing facilities, which must be preheated with expensive fossil fuels during cold seasons. Even where radon is not a concern, installation of appropriately-sized SRRS systems could provide solar-heated intake air during daylight hours, traditionally the most active industrial period. Residential SRRS applications can be installed with individually built or commercially manufactured solar panels, duct work, and fans; larger applications can be designed with multiples of such equipment or custom-fabricated sheet metal forms and glazing.

A related device well-suited to commercial or industrial applications requiring high ventilation rates is the new "unglazed transpired solar collector," hailed as the most efficient active solar heating system ever designed (Kutscher 1992), which could easily be incorporated into the SRRS strategy. Available commercially under the trade name Solarwall,[10] the collector consists of black-coated perforated (transpired) aluminum without glass or plastic glazing and typically covers the entire south side of a building; warmed fresh air drawn through the perforations is delivered into the building's ventilation system. Transpiration increases the absorber-air stream heat transfer coefficient; the glazing is eliminated because heat that might ordinarily be lost to natural convection or the wind is captured by the high-speed suction flow through the holes, resulting in improved efficiency and a lower installation cost for large-scale applications. However, compared to 4 × 8 ft glazed solar air collectors capable of delivering outdoor air warmed to 35-55°C at 3.5 cm^3/s (75 CFM), Solarwalls requiring large surface areas and high ventilation rates to reduce wind losses may not be as applicable to single residential housing retrofits.

The custom control units devised for this study can be improved in several respects: dials or program keys to set temperature set points can be easily added; a mode to limit radon-trigger operation to reasonable temperatures could be devised; and LED displays similar to those on electronic furnace thermostats showing current and average solar panel temperatures and system operation duration could serve to inform the occupants of energy gains/uses. Utilizing solar photovoltaic panels to power the fan, controls, and radon monitor is the logical next step in SRRS development and would further reduce operational costs and energy use; both the control unit and MTL Radon Alarm could easily be configured to be powered directly by DC. Heat recovery devices could be added to buffer cold outlet air; the SRRS could be used to pre-heat air-to-air heat exchanger inlets to prevent freezing. Heat storage, solar water heating, and active solar cooling systems would also greatly enhance the system's energy benefits.

To improve SRRS performance at the leakier homes studied, upper-story insulation should be added and seals tightened around windows and doors with weather stripping and caulking; ensuring air-tight doors between basements and living spaces at all houses may provide a barrier for radon-laden air and help preserve the pressurization effect of SRRS operation. Basement depressurization can also be minimized by sealing return furnace ductwork, creating a direct outdoor air supply for the furnace intake, and replacing combustion appliances with electric. Dampers should be installed on SRRS discharge outlets to prevent flow of basement air outdoors during non-operation; higher capacity fans with variable inlet dampers allowing indoor air to recirculate through the solar collector for reheating

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[10] Conserval Engineering Inc., 200 Wildcat Rd., Downsview, Toronto, Ontario M3J 2N5.

during periods when pressurization is not needed (controlled by a pressure transducer-based electronic signal) could allow both greater radon reduction and energy benefits.

This study establishes the SRRS as an effective radon mitigation technique that can reduce radon in almost all cases and can obtain concentrations below the EPA guideline in existing dwellings with elevated closed house radon levels. While radon reduction and energy efficiency will undoubtedly vary from installation to installation, improved indoor air quality and energy benefits are expected in all cases. With recommended improvements, the SRRS has the potential to be an ideal indoor air quality management system as it provides pressurization to reduce radon infiltration and backdrafting potential, ventilation to dilute persistent radon as well as other indoor air pollutants, and energy savings at low installation and operational costs.

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