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SOLAR RADON REDUCTION AT SIX HOMES IN NORTHEAST IOWA

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ABSTRACT

Growing concern about radon lung cancer risks, carbon monoxide poisoning, and the "sick building syndrome" have increased demand for improved indoor air quality. Through solar pre-heating of ventilation air, the Solar Radon Reduction System (SRRS) provides energy benefits with lower installation costs than conventional air-to-air heat exchangers and sub-slab suction approaches. Indoor air quality is improved through dilution, combustion appliance make-up air, pressurization, and reduced radon infiltration through induced-draft solar air collectors drawing supply air from outdoors. Installed at six homes in Waterloo and Cedar Falls, Iowa, the SRRS was found to significantly reduce radon reductions in all houses with energy benefits and improved overall indoor comfort. Up to 73% reductions from closed house levels as high as 20.9 pCi/L were achieved.

1. INTRODUCTION

Increased insulation and weatherization have been found to have detrimental effects on the quality of indoor air due to limiting the frequency of natural air changes. The U.S. Environmental Protection Agency (EPA) warns that improper ventilation can concentrate contaminants which would otherwise escape through leaks and cracks, and many indoor environments may be dangerously polluted by these toxic chemicals and gases. Tightened to conserve energy, a growing number of homes, buildings and schools are plagued by "sick building syndrome." The broad array of indoor pollutants includes airborne microbial spores, respirable dust, carbon monoxide, nitrogen dioxide, solvents, and volatile organic compounds (VOCs), but radon is the most insidious.

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An invisible, odorless radioactive gas produced from the natural decay of uranium-238 and radium-226, radon-222 is found in nearly all soils and occurs in varying concentrations almost everywhere on earth. Because radon is inert and does not chemically bind or attach to other materials, it can easily pass through all gas-permeable materials including concrete. Due to pressure differentials created by the "stack effect" of convection between basements and upper floors, radon is drawn indoors and can accumulate to hazardous levels.

The EPA has set a recommended "action level" for remediation at the radon concentration of 4 picoCuries per liter of air (pCi/L), which is comparable to having 250 chest x-rays per year. The EPA estimates that 1 out of every 15 U.S. homes have radon levels above this guideline (1), and in Iowa, an estimated 70-75% of homes have radon levels above 4 pCi/L (2).

The average charge for a contractor to lower radon levels in a home is about $1,200, although repairs required may range from $500 to $2,500 (1). Usual radon mitigation methods attempt to prevent naturally-occurring radon gas from entering a building by keeping the living space at a higher pressure than that of the contiguous soil. The earlier years of radon reduction research focused on depressurizing soil beneath the house, sub-slab suction, which uses fans oriented upward to apply suction beneath the foundation and vent exhaust air above the roof. Creating a pressure differential large enough to lower radon below the EPA action level often requires drilling several holes into the concrete slab and installing associated piping as well as sealing cracks, holes, and drains. This can result in considerable expense to homeowners and may also worsen other indoor air pollutants such as carbon monoxide.

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Less costly radon reduction approaches include pressurizing the indoors with supply-air fans and increasing ventilation with air-to-air heat exchangers (AAHX), which help dilute other contaminants as well as radon. However, all commercially available radon mitigation systems, including those equipped with AAHX, operate at net energy losses. A desirable indoor air management system would provide pressurization to reduce radon infiltration and backdrafting potential, ventilation to dilute persistent radon and other air pollutants, as well as energy-efficient heating or cooling.

2. PROJECT HISTORY

Seeking to combine the goals of energy conservation with low-cost indoor air quality improvement, one of the authors (R. J. Klein) devised and installed an original solar ventilation system to introduce fresh, pre-heated air indoors at a test home in Waterloo, Iowa in 1990. The Solar Radon Reduction System (SRRS), initially comprised of a 4' x 8' flat-plate solar air collector, ductwork into the central heating system, and a forced-draft mechanical blower, supplies outdoor make-up air for combustion appliances and stack effect losses to lower indoor radon levels through reduced infiltration and dilution. During cold seasons, the SRRS augments the existing heating system with solar-heated air to produce a net energy gain. In the summer, the system's blower provides low-energy cooling by ventilating the structure when outdoor temperatures drop below indoor levels (3).

Based on charcoal canister tests, SRRS operation lowered the first test home's initial basement radon level from 8.8 pCi/L to 2.5 pCi/L, a reduction of more than 70%. Heating costs were reduced and the general indoor comfort level was reported to be improved by the addition of solar-heated outdoor air.

An additional combination domestic water and air solar collector was installed in conjunction with the first SRRS to further extend heat gain and energy savings throughout the year. This homemade panel was constructed from debris recycled from a home improvement project; the glazing was previously used as sliding glass doors. A second complete SRRS was installed in 1991 at another test home in Cedar Falls, Iòwa, which originally exhibited a charcoal canister radon reading of 19.9 pCi/L in the basement. Construction and installation was accomplished at about 10% of the cost of comparable commercially available radon mitigation systems (3). In 1993, the SRRS design was issued U.S. Patent 5,186,160 and awarded research funds by the University of Northern Iowa's Reuse & Recycling Technology Transfer Center. A detailed instruction manual was developed for homeowners or contractors to build a complete SRRS — a solar panel installed on a south-facing wall, roof or as a free-standing unit together with a fan, wiring, and ductwork — for about $200, or less if constructed with recycled materials (4).

SRRS efficiency evaluations were first conducted in the winter of 1992-93 at test homes North and Lovejoy. Initial data collection included radon levels, hours of system operation, air flow rates, structure pressure differentials, temperature differentials, and estimated energy used. Radon data were collected in both homes as the mean of 4-hour intervals with two continuous radon data loggers (Honeywell Model 05-418) operated in accordance with EPA protocol (1).

The duration of SRRS and furnace operation was measured with elapsed time hour meters and recorded daily. The SRRS at North produced an air flow of either 65 or 130 cubic feet per minute (CFM), based on whether one or both of solar panel fans were in operation, adding 0.6 or 1.2 air changes per hour (ACH). Single SRRS panel operation at Lovejoy produced an air flow of 75 CFM, adding 0.4 ACH. The radon monitors were installed on the first floors at the test homes, which were maintained in "closed house conditions" with the SRRS deactivated and sealed, to establish baseline radon levels. Data indicated first floor closed house radon levels of 4.3 pCi/L for North and 8.0 pCi/L for Lovejoy (3).

The initial evaluations were conducted with the SRRS operating in a solar thermostat-driven mode, which achieves maximum energy benefits by introducing solar heated air inside only during times when adequate solar energy is available to heat outdoor air above the ambient indoor temperature, to a minimum of 25°C and often as high as 50°C. Compared to closed house radon concentrations, SRRS solar thermostat-driven operation was found to lower mid-day radon levels by an average of 29% at North and 24% at Lovejoy (3). During the 6-week test period, cloudiness and adverse weather conditions limited SRRS operation to less than one hour for about 15 days. Due to continued radon infiltration when the mitigation fans were off, night-time and early morning radon levels returned to near baseline levels.

The second operational mode evaluated the effect of the SRRS operating for additional periods, when home heating demands required furnace operation. This "solar/furnace-trigger mode" was achieved by wiring to activate the SRRS fan both with the solar thermostat and an electrical relay circuit to the central furnace fan, allowing system operation at intervals throughout the day and night as well as during solar insolation.

SRRS radon reduction effectiveness was expected to be related to the duration and volume of air introduced into the dwelling, and radon levels at Lovejoy directly correlated with hours of system operation (Fig. 1). Yet North showed little correlation between radon levels and hours of SRRS operation, which may be attributed to the rate radon resumed infiltration during non-operational periods due to leakiness and stack effect factors. Extended solar/furnace-driven SRRS operation achieved maximum radon reductions of 53% at North and 56% at Lovejoy compared to baseline levels.

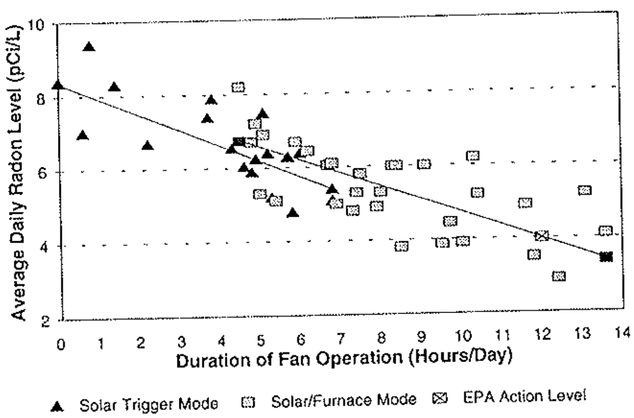

Fig. 1 Thermostat-driven and increased hours solar/furnace-trigger SRRS operation

Even with extended operation, the SRRS provided net conventional energy gain by solar heating air several hours per day. Based on BTU heat gain and loss calculations, energy savings for the 6-week period were estimated to be 1.1 MBTU at North and 0.2 MBTU at Lovejoy (3). Long-term energy savings were predicted to be greater, as solar insolation received during the test period was approximately half the average available in the region for January through March. Through graphical interpolation of the data from both test modes, SRRS operation (with a 75 CFM flow rate) for 12 hours per day was predicted to keep Lovejoy first floor radon levels below EPA's action level of 4.0 pCi/L (Fig. 1).

3. MODIFICATION & EVALUATION

Further testing in 1993-94 evaluated the flexibility of the SRRS in additional modified operational modes. Test home Lovejoy, equipped with continuous radon monitors on both the basement and first floor, was monitored over seven months with increasing levels of mitigation selected to coincide with EPA's radon mitigation action steps (5).

Data collected reveals incremental reductions for each of the test configurations (Fig. 2). The first mode, with the SRRS deactivated and periodic open house conditions, resulted in an average basement radon concentration of 3.2 pCi/L, signifying the minimum radon level achievable with natural ventilation. The second test period determined closed house radon levels of 8.0 pCi/L upstairs and 11.9 pCi/L downstairs, used as baselines to establish subsequent SRRS test modes efficiencies.

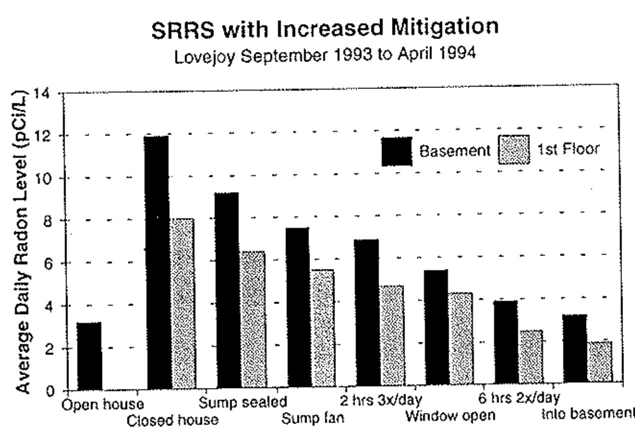

Fig. 2 Incremental radon reduction at Lovejoy

An open drain tile was identified as a possible direct radon entry point, so the sump pit was sealed and passively vented outdoors. The SRRS was then activated to discharge to the first floor in the solar thermostat-mode, which lowered radon levels an average of 22%.

In the fourth test mode, the SRRS remained in solar-thermostat operation while the sump pit ventilation was modified to include a 45 CFM forced-draft exhaust fan, a variation of sub-slab suction. Given constant SRRS operation, this more aggressive radon mitigation technique resulted in an additional 13% radon reduction.

During optimum solar insolation conditions, the SRRS operates approximately 6 hours. To evaluate consistent SRRS operation compared to weather-related efficiency, the system was timer-activated for three two-hour intervals spaced throughout the day. SRRS performance during actual solar-driven operation was found to be 85-92% of what was measured with consistent operation. This relatively high actual to ideal efficiency may result from reduced infiltration throughout the day due to the supply of low impedance appliance makeup air (3). The sixth test period incorporated natural basement ventilation with solar thermostat-driven SRRS operation. Lower radon levels were again obtained, and the difference between basement and first floor levels was also reduced.

Based on first-year results indicating that 12 hours of SRRS operation could achieve an average upstairs radon level of 4.0 pCi/L, for the next test the SRRS was timer-activated for six hours twice a day. One period coincided with optimum solar insolation to obtain maximum energy gain (9 am to 3 pm), and the other provided evenly-spaced mitigation during the night. This resulted in 2.5 pCi/L on the first floor, a 69% reduction, and 3.9 pCi/L in the basement, a 67% reduction. The SRRS was next modified to discharge fresh air directly into the basement rather than through the home's central heating system, and the basement window was closed to gain control over basement conditions. With the fan still operating six hours twice a day, this approach achieved an average reduction of 76% upstairs and 73% downstairs (3).

Longer-term evaluations of the 12-hour timer-based mode continued at Lovejoy through the summer of 1994 to compare the SRRS to the sump pit exhaust fan (Fig. 3). Basement radon levels in May-July with both fans running averaged 3.9 pCi/L. A two-week period in July when both fans were deactivated with closed house conditions while the homeowners were on vacation illustrates how quickly high radon levels return without mitigation. This 17.7 pCi/L average is even higher than the winter-time baseline obtained (11.9 pCi/L). The following three-month test with only the SRRS fan activated reveals larger daily radon ranges but a long-term average similar to combined SRRS and sump fan operation, 3.7 pCi/L. This documents stronger mitigation of SRRS ventilation and positive pressurization relative to sub-slab suction with the sump exhaust fan, and indicates that the lowest expected long-term basement radon levels at Lovejoy even with combined methods are in the 4 pCi/L range.

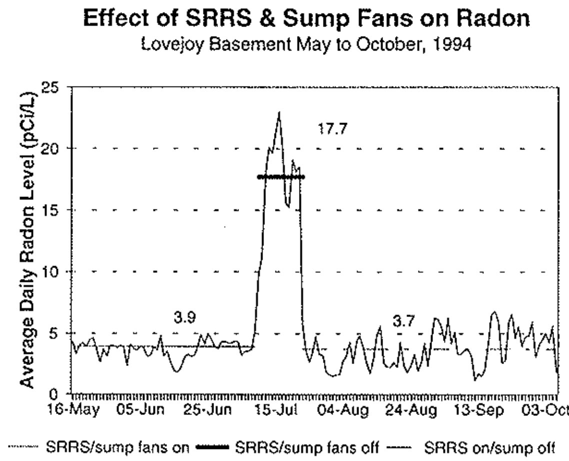

Fig. 3 Relative importance of SRRS and sump pit fan operation on radon mitigation

4. CURRENT RESEARCH

In order to simplify subsequent SRRS installations, newly available and affordable continuous Radon Alarms equipped with start/stop electrical relays (Monitor Technologies Model MTL-102 with MTL-106 mitigation controllers), which trigger fans to operate above pre-programmable radon levels, were incorporated into the SRRS strategy. In the fall of 1994, modified SRRS systems were installed at four additional test sites with elevated radon levels. Each house was equipped with data acquisition systems for continuous datalogging as well as MTL Radon Alarms, which activate the SRRS when radon levels reach 3.0 pCi/L. To maximize energy benefits, the units were wired in conjunction with electronic temperature sensors that additionally activate the fan either above (heating mode) or below (cooling mode) a preset intake temperature (Fig. 4). Data collected include radon levels, solar radiation, inlet and outlet temperatures and humidity, air speed, and indoor/outdoor pressure differentials at hourly intervals.

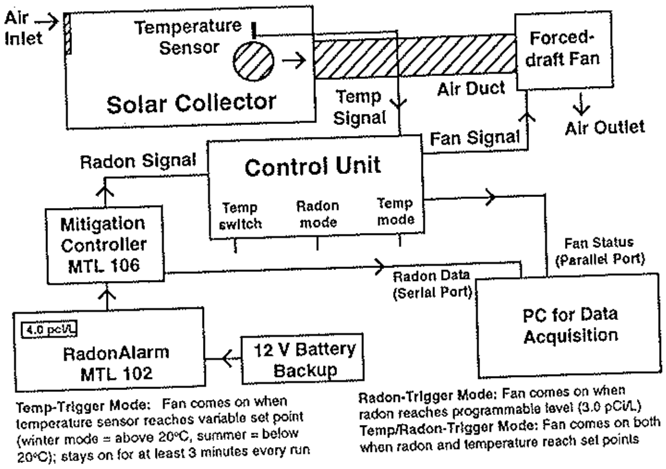

Fig. 4 SRRS controls and data acquisition system

Data was collected in December 1994-February 1995 with closed house, radon-trigger, and combination modes at the four new sites Sager, Byron, Vermont, and Washington as well as Lovejoy and a "control" house which had no radon mitigation installed. The two Honeywell monitors were used to record first floor radon levels at Lovejoy and Sager, and Air Chek mail-in charcoal radon testers were used to determine first floor levels at Byron, Vermont, Washington, and Control.

During the 10-day test periods, the SRRS was found to significantly reduce the average basement radon concentrations at every house compared to closed house conditions (Fig. 5). The Control showed natural variability in indoor radon over the five test periods, with a trend of increasing levels towards the end of the study. The temperature-based mode triggered the fan to operate 7.9 hours per day at Lovejoy, 7.2 hrs/day and Vermont, 4.3 hrs/day at Sager, 3.1 hrs/day at Byron, and 1.7 hrs/day at Washington.

The maximum response was seen at Lovejoy, the only house without combustion appliances, from levels of 20.9 pCi/L to 5.7 pCi/L in the basement (73% reduction) and 9.4 pCi/L to 3.0 pCi/L on the first floor (68% reduction). Reductions of 61% at Byron, 60% at Washington, 56% at Sager, and 48% at Vermont were also seen. Below-EPA action levels were achieved on first floors at Washington (2.9 pCi/L), Lovejoy (3.0 pCi/L), and Byron (3.9 pCi/L), and reduced first-floor levels at Vermont (5.0 pCi/L) and Sager (5.6 pCi/L) were close to this guideline.

The EPA recommends sealing cracks and other openings in the foundation as a basic part of radon mitigation, and overall improved weatherization together with higher capacity fans will likely achieve even greater reductions at these new houses, which were all shown to be more "leaky" than Lovejoy with blower-door tests. A further modification of activating the SRRS from Radon Alarms located on the first floor can provide a tighter control on living space radon levels, which may be required for houses such as Washington that appear to have higher radon levels upstairs than in the basement.

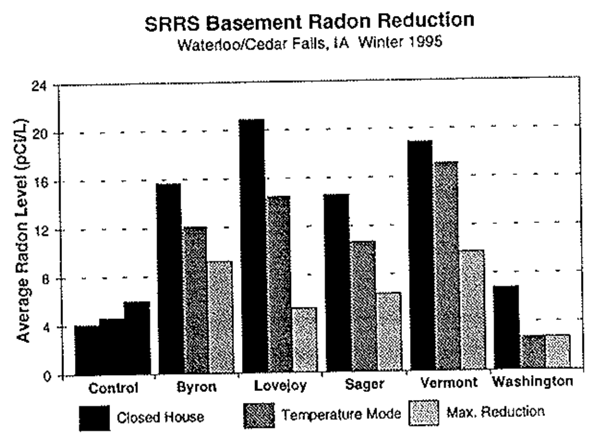

Fig. 5 SRRS fans activated both by temperature sensors and when radon levels reach 3.0 pCi/L

5. ENERGY CONSIDERATIONS

A major advantage of the SRRS over other radon mitigation methods is its ability to introduce solar-heated air into the home as well as to provide low-energy summertime cooling. This energy gain is optimized when system operation is limited to periods of adequate solar isolation during the heating season and during cool outdoor conditions in the summer. Extended SRRS operation introduces wintertime cold outside air during cloudy days and nights as well as warm and humid outdoor air during the cooling season.

Such heat gains and losses were calculated for Lovejoy's 12-hour timer-based operational mode for the month of March, 1994, which included 10 clear days, 11 partly cloudy days, and 10 cloudy days; an average outside temperature of 2°C; and an estimated average relative humidity of 50%. Fan temperature monitoring indicates that average SRRS outlet air can be assumed to be:

-38°C for 4 hours and 20°C for 2 hours on clear days;
-20°C for 6 hours on partly cloudy days;
-2°C for 6 hours on cloudy days; and
-2°C for all 6 hour nighttime operation intervals.

The enthalpy of SRRS outlet air was estimated to be 1.7 MBTU, and the enthalpy of indoor air at an average 22°C and 25% relative humidity replaced by SRRS air was about 2.7 MBTU (3). Thus approximately 1.0 MBTU of extra energy (300 kWh with an electric furnace) was required to heat SRRS outlet air to indoor ambient levels. Additionally, operating the 115 Volt, 0.59 Amp induced-draft fan 12 hours per day for 31 days required 25 KWh. At the volume-discounted rate of $0.03/KWh in Cedar Falls, IA, the SRRS energy expense for the month was about $9.75. The solar collector's heat input saved 510 KWh or $15.30 for the month compared to ventilation without preheating.

If each month resulted a similar net expense due to a heavier demand on either heating or air conditioning, the annual SRRS operating bill would be around $117. Compared to sub-slab suction systems, which do not introduce ventilation air into the house and typically cost $2,500, commercial SRRS installation is expected to cost $500. Using the same type of fan operating 24 hours per day, sub-slab would require 50 KWh/month or $42/year and possibly additional heating costs. Negating the time value of money, energy payback toward a sub-slab system would take at least 27 years, indicating that even in extended operation the SRRS is quite economical.

6. CONCLUSIONS

This research shows that the Solar Radon Reduction System was effective in reducing indoor radon concentrations with energy savings at six homes in Northeast Iowa. Due to the ventilation, air supply, and pressurization principles incorporated in SRRS operation, radon reduction efficiency was related to the duration of system operation and building leakiness.

In order to meet the EPA radon action level, modified modes of SRRS operation tested in conjunction with other radon mitigation techniques achieved greater reductions. Venting the sump pit with a forced-draft exhaust fan, a low-cost version of sub-slab suction, was shown to have little additional effect with the SRRS timer-activated for 12 hours per day. SRRS direct basement discharge was a significant improvement in terms of radon reduction and indoor comfort levels, rendering fan operation during less than ideal temperature conditions less noticeable to occupants. In addition, basement walls may prolong energy benefits and buffer losses. SRRS operation at Lovejoy for two 6-hour periods per day exceeded predicted effectiveness with an average living space radon yield of 2.5 pCi/L.

The SRRS shows promise as a radon mitigation technique that can reduce radon in existing dwellings with elevated levels and can obtain concentrations below the EPA action guideline in most cases. 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. Compared to other radon mitigation options, the SRRS offers occupants control over system operation to balance energy demands and desired radon reduction, improvement in overall indoor air quality and comfort, and low installation and annual operating costs. These advantages suggest more homeowners may be likely to install solar collectors and radon mitigation systems and, once installed, be less likely to discontinue their operation.

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