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Radon reduction, improvement of indoor air quality, and energy savings through an original solar ventilation system

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RADON REDUCTION, IMPROVEMENT OF INDOOR AIR QUALITY, AND ENERGY SAVINGS THROUGH AN ORIGINAL SOLAR VENTILATION SYSTEM

An Abstract of a Thesis
Submitted
In Partial Fulfillment
of the Requirements for the Degree of
Master of Science

Heather E. Rhoads
University of Northern Iowa
July 1995

ABSTRACT

This study evaluated the improvement of indoor air quality and energy savings achieved by an original solar ventilation system installed at test sites exhibiting elevated radon levels. Conventional residential energy conservation measures that limit air exchange rates between the indoors and outdoors have been shown to increase concentrations of radioactive radon decay products as well as other indoor air contaminants. Growing concern about radon lung cancer risks, carbon monoxide poisoning, and the "sick building syndrome" have increased demand for improved indoor air quality. Due to added heating and cooling loads, ventilation generally incurs substantial installation and operational costs. All commercially available radon mitigation systems, even those equipped with heat recovery devices, operate with net energy loss, and few alleviate other indoor air pollutants.

The ventilation system investigated combines energy conservation with low-cost radon reduction and indoor air quality management. Drawing on established mitigation techniques of ventilation, air supply and pressurization, the Solar Radon Reduction System (SRRS) provides energy-efficient make-up air for combustion appliances and stack effect losses. Indoor air quality is improved through dilution, slight pressurization, and reduced radon

infiltration with induced-draft ventilation. Solar heating of intake air enables the SRRS to operate with energy gain during cold weather, and the blower provides low-energy summertime cooling when outdoor temperatures drop below indoor levels.

The system was installed at six homes in Waterloo and Cedar Falls, Iowa, and a detailed assessment was conducted of the extent that the SRRS reduced radon levels and provided energy savings as well as how the system could be improved. Blower door tests were initially conducted to characterize the airtightness of each house. Electronic control units to trigger system operation based on radon levels and intake temperatures were devised, and PC data acquisition systems were installed at each site. The research methodology included synchronized hourly radon concentrations collected at the test homes and a "control" house maintained with closed conditions over five 10-day test periods. Operational modes tested included radon-trigger, temperature-trigger, and combined trigger system performance. Outlet temperatures and fan status were continuously recorded at five test homes, and dataloggers were additionally placed at two of the sites to measure inlet, outlet and basement temperature and humidity, solar radiation, and outdoor-basement pressure differentials. Fan rates were added to infiltration estimates for each house to determine system effects on house air time constants.

The SRRS was found to improve overall indoor air quality with energy benefits and to significantly reduce radon, up to 73% from closed house levels as high as 21 pCi/L. SRRS effectiveness was found to be related to the duration of system operation and dwelling leakiness; increased weatherization and fan capacity appear to enhance pressurization and dilution gains. An inverse correlation of winter temperatures and solar availability was found to be beneficial for solar heat collection. The control house exhibited fluctuating radon levels apparently due to weather-related factors, which correlated closely with radon trends particularly at the more leaky test sites. Thus a separate closed house was found to serve as an appropriate reference for simultaneous multi-home remediation comparisons. This study shows the SRRS is a promising energy-efficient indoor air improvement technique that can attain radon concentrations below the EPA guideline in existing dwellings with elevated levels.

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This Study by: Heather E. Rhoads

Entitled: RADON REDUCTION, IMPROVEMENT OF INDOOR AIR QUALITY, AND ENERGY SAVINGS THROUGH AN ORIGINAL SOLAR VENTILATION SYSTEM

has been approved as meeting the thesis requirement for the Degree of Master of Science in Environmental Science.

14 Jul '95

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Date

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I INTRODUCTION

Energy conservation measures such as increased insulation and weatherization have been found to detrimentally affect indoor air quality (IAQ) due to limiting the frequency of natural air changes. As commercial and residential structures become more airtight to reduce heating demands, radon gas and other indoor air pollutants have a greater potential of accumulating to hazardous levels. Since U.S. residents typically spend 75-90% of their time indoors, the health of many people greatly depends on the quality of air in the indoor environment. Improved ventilation is necessary to combat the "sick building syndrome" in many homes, buildings, and schools (Mattill 1993).

However, due to larger heating and cooling loads, additional ventilation increases energy use, seemingly placing IAQ and energy conservation at odds. Even with air-to-air heat exchangers, which recover some thermal energy from exhaust air, ventilation is typically accomplished with a net energy loss; direct ventilation fans incur even more severe energy penalties. Nevertheless, energy efficiency as well as the development of renewable energy sources are essential for reducing modern society's dependence on polluting energy sources.

Conventional radon mitigation techniques have energy needs such that operating systems in every U.S. home with elevated radon would require the equivalent of several new nuclear power plants. Most approaches to reducing radon do not address other indoor air pollutants, such as carbon monoxide from backdrafting of combustion appliance flue gas, and may even increase their accumulation through depressurization and short-circuiting. Moreover, installation and operational costs are prohibiting for many residents, particularly renters and low-income homeowners.

Thus a desirable IAQ management system would provide pressurization to reduce both radon infiltration and backdrafting, as well as ventilation air to dilute persistent radon and other indoor air pollutants present. In addition, such a system requiring low installation and operational costs, providing net energy gain, and flexible for structure size or pollution levels, would be ideal. Widespread public concern regarding lung cancer risks has fueled the current $8 billion U.S. radon mitigation market as well as demand for more dynamic radon reduction techniques (Renken and Konopacki 1993).

With support from the University of Northern Iowa's Environmental Science Program and Recycling Reuse Technology Transfer Center, this study investigates the use of solar collectors to preheat fresh outdoor supply air and thereby improve indoor air quality. An original approach to ventilation, the Solar Radon Reduction System (SRRS), is evaluated as an inexpensive and energy-efficient method of reducing radon and other indoor air pollutants. These potential benefits were identified in preliminary studies of the SRRS installed at two homes (Klein and Olson 1993).

In order to be approved by the U.S. Environmental Protection Agency (EPA) for installation by radon mitigation contractors, new systems must be evaluated according to EPA Protocols for Diagnostic Measurements in Radon Mitigation Demonstration Projects, which cover diagnostic testing and data collection. The current research was undertaken following the specified protocols on four additional test homes, as both a field test and demonstration for local health departments and non-profit organizations to renovate affordable housing for radon and energy-efficiency.

The following three chapters provide substantial background information on energy concerns, radon reduction, and indoor air quality and review the previous SRRS study. Chapter 2 examines environmental consequences of current energy practices, the common conservation approach of weatherization, and causes of the "sick building syndrome." Radon is identified as a key indoor air pollutant, and its driving forces, prevalence, regulatory status, and health effects are described in detail. Chapter 3 reviews pertinent published studies and reports on standard radon mitigation techniques and solar air heating, with special focus on research similar to the current study.

A detailed history of the SRRS project is provided in Chapter 4, including descriptions of the system design, initial evaluations, modifications, and energy benefits. This chapter includes a reanalysis of the earlier data that raises additional questions such as the need to account for the influence of time-dependent external factors. While the SRRS was shown be a promising radon mitigation strategy, the factors affecting its applicability on a range of installations was unknown.

An overview of methodology, experimental design, and instrumentation is reported in Chapter 5. 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. In all, a "control" and five test houses were evaluated under closed conditions and various SRRS operational modes to determine radon reduction effectiveness and energy benefits. Numerous parameters were monitored with computer-controlled data acquisition systems including instantaneous radon alarms and temperature, humidity, pressure, solar insolation, and air flow sensors.

Results are presented and interpreted in Chapters 6 and 7, respectively. Chapter 6 includes a complete set of charts containing calibration and radon mailer results; ventilation levels achieved; real-time radon, temperature, fan and pressure data; statistical distributions of hourly radon levels based on analysis of variance; and time-weighted averages of additional parameters monitored. Chapter 7 analyzes the ability of the "control" house to model external factors, effects of pressurization on radon infiltration, and SRRS energy benefits. Finally, Chapter 8 summarizes implications of the investigation and offers recommendations for design improvements and additional installations.

Ultimately, this thesis addresses the connections between housing, health, and the environment through the practical application and examination of an "appropriate" technology. The concept of appropriate technology emerged during the 1970s as a new approach to economic and social development (Carr 1985). E. F. Schumacher, Rachel Carson, John Kenneth Galbraith and others warned of the dangers of environmentally careless growth and argued that both developing and "developed" countries should move toward technologies appropriate to a sustainable, balanced economy. Appropriate technologies, those suited to their environment, were envisioned as requiring low capital costs, having organizational simplicity and high adaptability, using natural resources sparingly and local/recycled materials whenever possible, involving decentralized renewable energy sources, and providing employment and affordable final products. Equipment could be home-made or produced in small shops, and practical instructions would be obtainable free or for a low one-time fee.

In the words of eco-housing advocate David Pearson (1989, p. 12):

> To support personal and planetary health, we need healthy and conserving homes . . . homes that are designed not to damage the environment but to bring positive regeneration to it; homes, in fact, that are not sick, but are healing places for body, mind, spirit, and planet.

As an ideal "appropriate technology," the SRRS supplements existing heating and air supply systems with low-cost solar collectors, serving both long-term financial and health interests of residents and the environment.

II RATIONALE

A change in residential energy practices is crucial for long-term planetary and personal health. This chapter provides arguments for the necessity of both energy efficiency and indoor air quality. Steps that can be taken to minimize heating costs and causes of the "sick building syndrome" are described. As a key indoor air pollutant, radon is highlighted for detailed examination.

Residential Energy Use

Many global environmental problems can be attributed to resource consumption and, ultimately, current energy practices. Combustion of fossil fuels alone releases staggering amounts of carbon dioxide, carbon monoxide, ozone, nitrogen and sulfur oxides, hydrocarbons and particulate matter into the atmosphere, leading to smog, acid precipitation, stratospheric ozone depletion and an increased greenhouse effect. Widespread soil contamination, oil spills, leaking underground storage tanks, coal and uranium mine drainage, stockpiling radioactive waste, habitat loss and mercury poisoning due to large-scale hydropower, decimated old growth and tropical rainforests, and even the Persian Gulf War can all be linked directly or indirectly to energy production and use. Indeed the effects of wood, coal, oil, gas, hydroelectric and nuclear fuels, which power much of the world, may be the primary driving force of environmental degradation (In-fei Liu 1993).

Industrialized nations expend ten times as much energy and produce sixteen times as much pollution per capita as Third World countries. As 6% of the world's population, the U.S. is responsible for a full one-third of global nonrenewable resource depletion (Sager 1990). Nationwide, about one-third of all energy consumed is for space and water heating; residential heating alone accounts for one-fifth (Craig 1988). This is one outcome of the "American dream": millions of large, detached, single-family homes which use more energy than any society's shelters have ever before (Hayden 1984). Trees that might have provided shade and wind protection are leveled, and the same houses are built facing every direction regardless of orientation toward the sun. Standardized floor plans and large picture windows create patterns of heat gain and loss which are compensated with year-round air conditioning/heating.

Although energy conservation and renewable, non-polluting sources are clearly needed, research and government budgets have given scant attention to developing solar, wind, and biomass resources while focusing priorities on nuclear power and locating fossil fuel reserves with increasing technological sophistication. Oil, coal, and natural gas use are now growing so much that CO_2 emissions are predicted to rise 70% globally by 2020 (Steger 1990).

Environmental consequences of continued inefficient fossil fuel use necessitate that barriers to energy conservation be overcome (Ledbetter 1988). The current oil glut has decreased consumer demand for energy efficiency, a greatly under-utilized environmental protection strategy. Both a change in accounting practices to reflect environmental costs and a reduction in subsidies toward polluting energy sources are needed to increase financial benefits for energy conservation and investment in renewables.

An important consideration in renewable energy and conservation products is consumer access to the technology, particularly affordability. A wide range of new energy-saving and solar technologies have become available, from fluorescent bulbs and solar security lights to wind generators and tracking photovoltaic panels; fully equipped homes can now be built "off the grid." Such large-scale projects are not a practical reality for most people, nor are earth homes and "bioshelters" touted by some environmentalists. Minimizing heating bills can be important for lower income residents; yet private landlords generally prohibit alteration, and state-funded housing renovations rarely address energy efficiency.

Still, substantial energy savings can be achieved in almost every home. Space heating accounts for 40-60% of energy used in older-style houses; 20% heats water, and 15-30% is used for cooking, lighting, and electrical appliances. An average house loses 30-40% of its supplied heat due to leaky construction. Windows and doors lose a further 20%, walls 15-25%, roofs and ceilings 12%, and 10% is lost through ground floors and basements (Pearson 1989). The first step in reducing residential fuel consumption is generally improving the structure's insulation and weatherstripping, which alone can save up to half the energy spent by furnaces and water heaters. An uninsulated, heated basement can represent up to 50% of the annual heat loss in a house which is well insulated above the grade. National building standards now recommend foundation insulation in cold climates (Christian 1991). Indoor air exchanges with outdoor air every hour or faster in a typical older house; tight seals and construction can reduce this to once every three hours or more (Pearson 1989). As Pearson (1989, p. 8) maintains, "it is only by changing our own lives and homes that we can begin to save the environment."

Weatherization and Sick Building Syndrome

Triggered by the 1970s oil embargoes, growing numbers of homeowners and builders have done just that: between 1980 and 1982 alone, over 700,000 houses were weatherized, and current construction practices produce even tighter structures (Brambley and Gorfien 1986). However, sealing cracks and increasing insulation may also drastically reduce the quality of indoor air by limiting the rate of natural air changes. Radon gas and other air pollutants such as carbon monoxide and volatile organic compounds (VOCs) have caused growing public concern as homes, buildings and schools have been tightened to conserve energy. In the past decade, indoor air quality has become a major issue due to greater awareness of health risks and heavier use of building materials emitting harmful gases as well as increased airtightness of homes and buildings (Turner and Brennan 1985). In 1983, the U.S. Congress granted a special appropriation for an EPA research program to define and characterize IAQ concerns (Sanchez et al. 1987).

The U.S. EPA now warns that low air exchange rates can concentrate contaminants that would otherwise escape through leaks and cracks, and many indoor environments, particularly energy-efficient homes and under-ventilated office buildings, may be dangerously polluted by toxic chemicals and gases (Dulley 1994). Combinations of indoor and outdoor pollutants are affecting health in many ways: allergies and environmental illnesses are on the rise, and immune disorders and cancers are among modern industrial society's leading killers. One study of residential weatherization and radon estimated that for the average U.S. home, retrofitting that reduces natural ventilation from 1 down to ½ air changes per hour increases the risk of fatal lung cancer by 115% (Brambley and Gorfien 1986). Another survey found that reported radon levels were 35% higher in well-weatherized houses than in leaky ones (Cohen and Gromicko 1988). Symptoms such as headaches, nausea, eye irritation, tension, breathing difficulties and fatigue are increasingly being linked to building-related pollutants; the EPA estimates that the "sick building syndrome" costs the nation billions of dollars per year in public health problems, absenteeism and reduced productivity (Mattill 1993).

However, the goals of energy conservation and indoor air quality are not necessarily mutually exclusive. The National Institute for Occupational Safety and Health has determined that 52% of all sick building complaints were caused by inadequate ventilation and dirty, contaminated air conditioning systems. A study comparing a large heating, ventilation and air conditioning (HVAC) unit before and after cleaning and balancing found resultant savings of 5.1 amps in energy consumption, translating into an annual energy savings of 37,143 KWH (kilowatt-hours). Increased heat transfer efficiency and reduced pumping energy accounted for an additional annual reduction of 57,706 KWH. At an average cost of 6.1¢/KWH, the first year savings in this single HVAC unit totaled $5,786 (Hansen 1992).

A residential radon study which statistically controlled soil types could not determine a significant relationship between weatherization and radon levels (Chi and Laquatra 1989). The authors maintain that soil permeability is a better indication of indoor radon, and that media hype about detrimental impacts on IAQ of weatherization has unnecessarily reduced the push for residential conservation efforts. Of 245 randomly selected houses, those on sandy soils and gravel had higher radon than those on poorly drained soils. Air exchange rates have also been found to be poor indicators of radon, as increased convection can draw excess air through soil.

In addition, rental units and low-priced homes were more likely to have elevated levels of indoor radon than their high-priced counterparts (Chi and Laquatra 1989). Because high-income homeowners have taken more action regarding radon, specific outreach and educational programs targeting lower socioeconomic groups were recommended. The need for a better public understanding of building dynamics was identified, as pollutant sources can substantially affect leaky houses, and tight houses may not necessarily have IAQ problems if adequate ventilation and no strong sources are present (Du Pont and Morrill 1989).

The broad array of indoor pollutants includes: radioactive radon gas; formaldehyde fumes from furniture, carpet, paneling and curtains; other volatile organic compounds (VOCs) emitted from structural materials and finishes; respirable dust and asbestos fibers; the combustion products carbon monoxide, nitrogen dioxide, and cigarette smoke; and vapors from hair sprays, perfumes, deodorants, air fresheners, food, and pesticides.

Biological pollutants include dust mites, molds, airborne fungal spores, bacteria, and other organisms which flourish in humid, stagnant environments. The toxic effects of air contaminants appear to be additive, so that an irritating atmosphere may be produced by the combined effects of many minor pollutants. Indoor relative humidities above 60% contribute to thermal discomfort and odor perception, while low humidity (under 35%) in winter is a recognized contributor to school absenteeism (Wheeler 1992). Circulation rates of 0.75 cubic feet per minute (CFM) per square foot are suggested to eliminate the perception of "stuffiness" (Hansen 1992).

The danger of backdrafting and venting of combustion appliance gases into living spaces has recently received considerable media attention, as carbon monoxide poisoning has been found to kill 300-400 and injure thousands of people each year (Du Pont and Morrill 1989). Yet perhaps the most insidious indoor contaminants are radon gas and its by-products, which are harder to detect and reduce at the source than other airborne pollutants, are difficult to filter, and have established health risks.

Key Indoor Air Pollutant: Radon

An odorless, colorless, tasteless radioactive gas produced from the natural decay of uranium-238 by way of radium-226, radon-222 is found in nearly all soils and occurs in varying concentrations almost everywhere on earth.[1] High radon levels have been traced to radioactive granitic and sillimanite deposits, as well as to coarse glacial sand and gravel. Soil porosity has been identified as a critical determinant of radon levels in soil gas; radon has been found to escape at higher rates from sand particles with large surface areas than from solid bedrock (Turner and Brennan 1985). Radon can move easily through permeable soils, allowing it to accumulate from a large area beneath and surrounding a house. Less permeable soil does not permit as much soil gas mobility, so clays and silt act as effective radon barriers (Chi and Laquatra 1989).

As a noble gas, radon cannot be seen, tasted, or smelled, and it is readily soluble in water.[2] Thus groundwater may also carry high levels of radon. Radon can enter the indoor environment via several paths, including emission from building materials. Elevated indoor radon levels were first discovered in the mid 1960s in Colorado where uranium mill tailings were used as backfill material and poured into concrete blocks used in foundations (Craig 1988). It can also outgas from the water supply, when water is exposed to air during showering and other household or industrial uses, and from utility natural gas.

[1] Every square mile of soil to a depth of 6 inches is estimated to contain on average 1 g of radium (Lide 1992).

[2] Radon has a solubility of about 2×10^{-4} at 20°C; lower than that of CO_2 (7×10^{-4}) but higher than O_2 (2.5×10^{-5}) (Lide 1992).

More typically, radon originates as gas in soil and infiltrates indoors through floor drains, hollow-block walls, cracks in concrete walls and floors and spaces around pipes, gaps and joints in building materials, or crawl spaces. Most entry routes are in the basement or areas with surface area exposed to surrounding soil. Because radon is chemically inert, it can pass through all gas-permeable materials including concrete. It is drawn indoors by pressure-related forces created by the "stack effect" of warm air convection upwards, wind loading on the building shell, and operation of exhaust fans and combustion appliances. Resulting air currents can create negative pressure in the lower sections of the house relative to outdoors, pulling air in through soil (Fig. 1). Once trapped inside, radon can accumulate to hazardous levels, particularly in cold seasons or during rainy weather conditions (Du Pont and Morrill 1989).

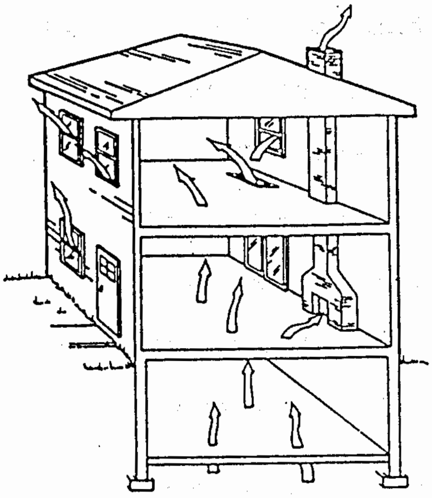

Figure 1. The "stack effect" phenomena, caused by warm air rising and escaping out upper story cracks (Lafavore 1987)

Scope of Radon Problem and Legislation

First established in 1985, the EPA's Radon Action Program budget rose to over $22 million by 1991. Based on a 1987 10-state survey of 11,600 houses, the EPA estimated that 8-12% of the nation's housing had radon levels above its recommended "action level" of 4 picocuries[3] per liter of air (pCi/L). Although the EPA does not statutorily regulate indoor radon levels, its action guidelines are widely considered national recommendations on acceptable levels. In many regions, radon testing is routinely performed during real estate transfers; property owners are faced with potentially paying for mitigation (NRC 1991).

A 1988 EPA survey found nearly one in three U.S. homes with elevated radon levels, prompting the Surgeon General and the Centers for Disease Control to urge testing of all houses and apartments below the third floor. An EPA survey of 130 schools among 16 states found that 54% of the schools had at least one "unsafe" room and 19% of the 3,000 classrooms measured high; the EPA has also called for testing of all schools (NRC 1991). The radon danger in schools and most other types of non-residential buildings is now believed to be as widespread as in homes (Freije 1990).

The EPA now estimates that 1 out of 15 homes throughout the U.S. have radon levels of 4 pCi/L or more (U.S. EPA

[3] A curie (Ci) equals 37 billion radioactive decays per second; one picocurie is 10^{-12} Ci or 3.7×10^{-2} disintegrations per second.

1993). Of new houses built in the U.S. each year, roughly 60,000 are likely to have radon levels above the EPA guideline (Renken 1994). Geographically, the highest potential for elevated radon in the U.S. exists in the Upper Midwest, the Great Plains, and the East Central states, although most of the remaining states also have variable elevated levels (U.S. EPA 1994). In Iowa, an estimated 70-75% of homes have radon levels above 4 pCi/L (Eckoff 1990).

Data gathered from over 4,000 U.S. homes in 1989-1990 showed that the average nationwide indoor radon level is 1.3 pCi/L, compared to an average of 0.4 pCi/L outdoors (U.S. EPA 1992). In the Indoor Radon Abatement Act of 1988, the U.S. Congress set the perhaps unrealistic long-term goal that indoor radon levels be no more than outdoor levels. The Indoor Radon Abatement Reauthorization Act (S 657) and the Radon Awareness and Disclosure Act (HR 2448) under consideration include sections addressing disclosure of radon information, stating that sellers and lessors of real estate shall provide purchasers with radon pamphlets, information on the presence of known radon, and radon evaluation reports if available; the Reauthorization would also permit purchasers a 10-day period to conduct radon testing (Radon News Digest 1993).

Several states have enacted or proposed state laws requiring contractors to be certified in radon testing and mitigation, including the District of Columbia, California, Indiana, Iowa, Kentucky, Nevada, Rhode Island, and West Virginia. Seven states currently require real estate agents or sellers to provide radon information to potential buyers; Pennsylvania has proposed a bill requiring owners of residential real estate to test for radon. Virginia has enacted and Minnesota has proposed laws requiring schools to test for radon (Radon News Digest 1993).

Health Effects of Radon Exposure

The major health concern associated with exposure to elevated radon levels is an increased risk of contracting lung cancer. Although scientists dispute the precise number of deaths due to radon, major health organizations including the Centers for Disease Control, the American Lung Association, and the American Medical Association agree that radon causes thousands of preventable deaths every year; the National Cancer Institute has declared radon exposure the leading cause of cancer among non-smokers (U.S. EPA 1993). At 8.9 radioactive decays per minute, the EPA's mitigation "action level" of 4 pCi/L is comparable to the lung cancer risk of 250 chest x-rays per year or of smoking ten cigarettes per day (U.S. EPA 1991).

Of the three radon isotopes, radon-219 and radon-220 have half-lives measured in seconds and consequently decay before they move anywhere; radon-222 decays with a half-life of 3.82 days into a series of short-lived radioisotopes collectively referred to as radon progeny (formerly called radon daughters) or radon decay products (Fig. 2). Radon-222 is the first product formed in the radioactive decay of radium-226, which is itself the fifth decay product of uranium-238; it eventually decays to lead-210. Two of the short-lived products in the major decay chain, polonium-218, which has a decay energy of 6.0 MeV, and polonium-214, 7.7 MeV, emit alpha (α) particles (Hanson 1989).

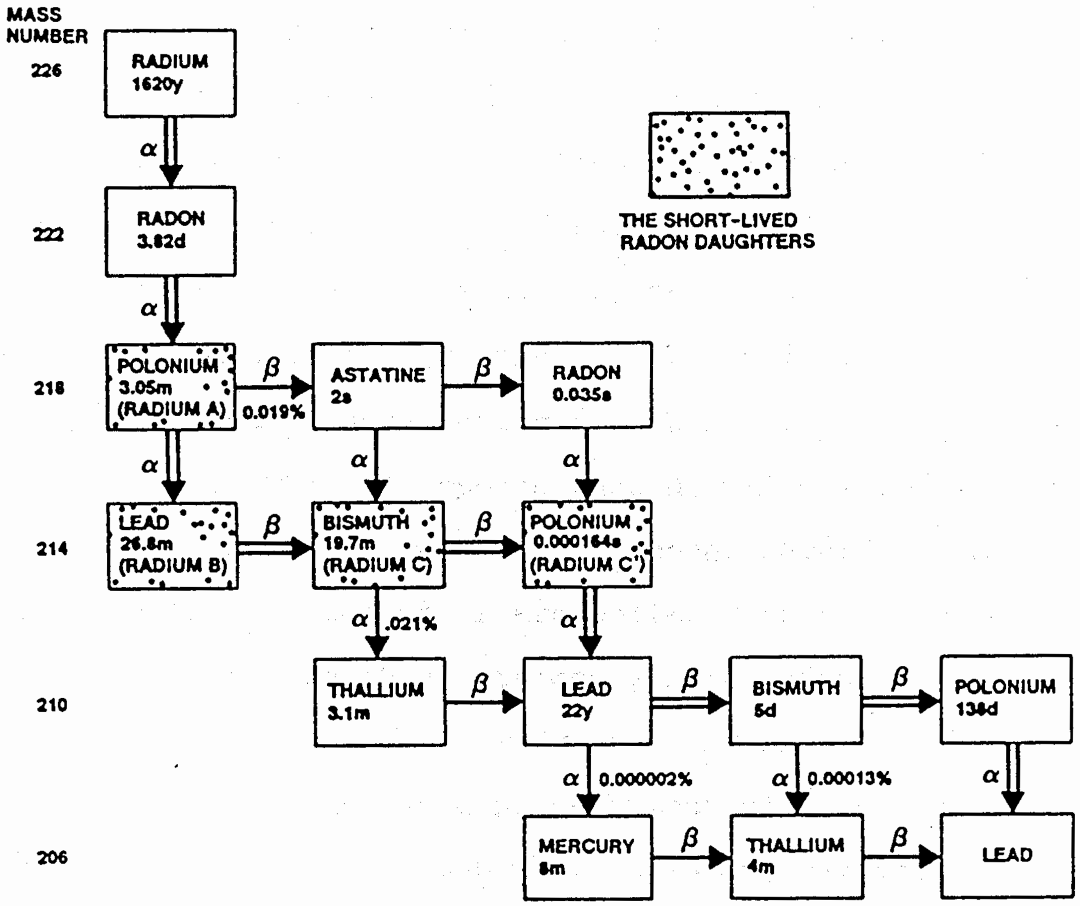

Figure 2. Radon-222 decay series.
The major decay route is the unbranched chain marked by double arrows; half-lives are shown for each isotope with s = second, m = minutes, d = days, and y = years (NRC 1991)

Unlike the inert gas radon, the solid polonium isotopes can attach to dust particles and are of greatest health concern. Upon inhalation, radioactive particles may become lodged in airways near some of the most cancer-sensitive cells in the human body. As the decay process continues, α-particle emissions release bursts of energy that can ionize lung tissue. Damaged cells can then multiply rapidly, resulting in lung cancer (Freije 1990).

Research is currently underway to find out if radon causes other kinds of cancer as well. A study comparing average radon exposures and rates for leukemia and other cancers in 14 countries identified significant positive correlations for childhood and adult leukemia, kidney cancer, melanoma, and prostatic cancer. Calculations for radon-derived α-radiation doses to bone marrow and skin supported a causal explanation for the correlations (Henshaw et al. 1992). The EPA reports that drinking water with high radon levels may also pose risks, though hazards from ingesting radon-laden water are believed to be much lower than those from breathing air containing radon.

Accounting for about 55% of all background radioactivity, radon gas exposes humans to more radiation than all other sources combined, including x-rays, cosmic rays and nuclear fallout (Freije 1990). Although radon is one of the few proven (Group A) carcinogens, the magnitude of lung cancer risk associated with residential radon exposure is still controversial. Most of the evidence about the effects of radiation on humans is from studies of atomic bomb survivors, uranium miners, nuclear accidents and radiation therapy; much less is known about the effects of chronic low-dose radiation exposure in homes (Turner and Brennan 1985). More than 100 years ago metal ore miners in Schneeberg, Germany, were found to develop intrathoracic malignancy, shown to be primary cancer of the lung; high radon levels measured in those and other mines in the early 1900s was confirmed as the cause of lung cancer through epidemiologic evidence from 20 different groups of miners (reviewed in NRC 1988).

Except at the highest levels, the lung cancer risk in underground miners has been shown to be related roughly linearly to exposure, and the combined effect of cigarette-smoking and radon exposure shows a synergism between the two carcinogens. Smokers in the highest exposure group of a recent Swedish study were 25 to 30 times more likely to develop lung cancer than nonsmokers in the lowest exposure group, a risk much greater than simply adding the risks of radon and cigarette smoke (Stone 1994). A 1988 report by the National Research Council found that smokers exposed to radon increase their risk of lung cancer by 10 or more times in comparison to non-smokers. Increased lung deposition of inhaled particles in smokers, among other factors, is thought to increase α-particle energy doses to central airways where lung cancers arise (NRC 1991).

The complex relationship between exposure to radon progeny and dose to cells in the respiratory tract, considered prime targets for carcinogenesis, depends on both biological and physical factors including characteristics of the inhaled air, airway, and breathing patterns, aerosol size distribution, and the proportion of progeny not attached to particulates. Smaller radioactive particles can penetrate and deposit much more effectively in the lung, and thus deliver a greater dose per given airborne activity.

Atmospheres with low dust or smoke particle concentrations have a high proportion of "unattached" radon gas molecules and tend to have higher overall rates of decay-product deposition (plate-out) onto building walls; this "sink effect" results in lower total airborne decay-product concentrations (Nero 1989). In well-insulated homes with low ventilation rates, the particle loading of air may be low, giving rise to a large unattached fraction. Particle-cleaning devices which remove decay products directly can also reduce airborne radon; however, many of the small/inexpensive air cleaners available are so ineffective that effects on radon exposures are irrelevant (NRC 1991). Combustion sources and humidification also affect activity-size distributions of radon decay products (NRC 1994).

Because the dose of α energy delivered to target cells cannot be measured directly, modeling approaches are used to simulate the process. Laboratory data has provided a solid information base indicating that radon α particles cause mutations in cultured cells, oncogenic transformation in cells in vitro, and tumors in experimental animals. A biophysical model based on cultured cell experiments has found to be consistent with the dose-rate effect observed in studies of animals and underground miners, which supports the validity of extrapolating data from radon exposures in mines to risks in residences (NRC 1994).

Epidemiologic studies have also been used to estimate lung cancer risks associated with indoor radon. However, an attempt to analyze three case-control studies conducted in New Jersey, Sweden and China found that pooling the data rendered the risk estimation so imprecise as to be consistent both with no effect and with the model based on underground miner exposures (Lubin et al. 1994). A second Swedish epidemiologic study (Pershagen 1994), one conducted in Canada (Letourneau 1994), and a widely-publicized one in Missouri (Alavanja et al. 1994) have recently been published; one in Iowa is forthcoming (expected 1997). Results range from no apparent association between indoor radon exposure and lung cancer to effects greater than anticipated from miner studies. Uncertainties in lifetime exposure estimates and other methodological problems potentially confound such studies so that a definitive, quantitative risk assessment is not anticipated (NRC 1994).

Recent advances in the molecular genetics of cancer raise the possibility that the densely ionizing α particles released by radon decay products produce characteristic genetic changes recognizable at the molecular level, constituting a "signature" of radon exposure. Oncogenes and tumor-suppressor genes from uranium miners and α particle-induced tumors in experimental animals are now being studied to explore this possibility. Preliminary evidence indicates that molecular changes characteristic of cancers induced by α particles may indeed be identifiable (NRC 1994).

Risk projections of radon-related lung cancer in the general population have widespread policy implications and currently serve as the basis for establishing action guidelines for judging the safety of the nation's homes, schools, and offices as well as for guiding potentially costly mitigation of unacceptable levels (U.S. EPA 1986a). Testing over the past 20 years has confirmed that radon is widespread indoors, reaching levels in some homes as high as those in mines of up to hundreds or even thousands of pCi/L (NRC 1994). The EPA estimates that radon accounts for 13,600 deaths per year, with an uncertainty range from 7,000 to 30,000, calling it the "highest cancer risk of any single environmental problem" (Freije 1990).

III LITERATURE REVIEW

This chapter provides an overview of current radon mitigation and indoor air quality strategies as well as solar air heating techniques. Specific focus is given to research on two systems similar to the SRRS: a basement pressurization/heat recovery radon reduction method, and commercial-scale solar pre-heating of ventilation air.

Radon Mitigation and IAQ Options

Continuous monitoring of indoor air contaminants is becoming more affordable by using specially designed testing devices. The EPA has published numerous guidelines and consumer booklets explaining the process of residential radon testing, including listings of EPA-approved test kits and testing companies certified through the Radon Measurement Proficiency Program (EPA 1993). The EPA also advises consumers with elevated radon levels to have their homes "fixed" by a trained radon mitigation contractor. EPA's Radon Contractor Proficiency Program (RCP) requires contractors to take training classes and pass an exam; state radon offices also provide lists of state-certified or RCP-approved mitigation contractors.

The EPA has also developed standards for controlling radon in new buildings, stating that incorporating basic radon prevention measures at the time of construction would increase building costs only minimally (U.S. EPA 1994). The

National Association of Home Builders estimates that 12% of the 1.3 million housing units built in 1990 included radon resistant features (MURC 1993). The EPA has proposed three levels of radon control for new buildings: passive systems, including physical barriers and open vent pipes to exhaust radon-laden air from beneath the structure; active systems, such as a forced-draft fan in the vent pipe; and stack effect reduction features that prevent upward air flow, including make-up air for combustion appliances and sealed chimney flues, plumbing chases, and attic access doors. The EPA has proposed that passive systems and follow-up testing be required for new construction in high radon potential areas, and that the systems be activated if test results are above acceptable levels (U.S. EPA 1994b).

Usual radon mitigation methods attempt to prevent naturally-occurring radon gas from entering a building by keeping indoor air at a higher pressure than that of the contiguous soil. To reduce radon infiltration and accumulation in existing structures, the EPA recommends natural ventilation, forced ventilation, sealing foundation cracks and openings, sub-slab suction, air supply, and heat-recovery ventilation (U.S. EPA 1986b).

Average radon reductions and installation and operating costs are summarized in Table 1, with information compiled from EPA (1992) and Du Pont and Morrill (1989). Sealing cracks and other openings in the foundation is a basic part of most radon reduction abatement, although sealing alone is not recommended as it has not been found to lower radon levels significantly or consistently. Tightening a building's shell and furnace ducts can also reduce the stack effect, aiding further radon mitigation steps which utilize pressure gradients as well as saving energy.

Table 1. Summary of Current Radon Mitigation Techniques

Control Technique	**Typical Radon Reduction**	**Installation & Operating Costs**	**Comments**
Sealing Cracks and Holes	0-90%	$100-2,000	May be impossible to seal all entry paths; enhances pressurization
Passive/Active Soil Depressurization	30-70% (PSD) 80-99% (ASD)	$800-2,500 $75-225/yr	Needs permeable soil; energy costs; can depressurize house
Sump or Drain-Tile Ventilation	70-95%	$550-2,500 $75-225/yr	Similar to PSD/ASD, danger in radon-laden air re-entering
Natural Crawl-space/ Basement Ventilation	0-50%	$200-500 energy penalties	Not practical in cold climates; makes basement unlivable
Basement Pressurization	50-99%	$500-1,500 $150-500/yr	Works best in tight houses; increases heating/cooling load
Heat Recovery Ventilation (AAHX)	50-80%	$1,200-2,500 $75-700/yr	Improves general IAQ, but flow may become unbalances; net energy loss

Since major structural modifications may be required, the average cost for a contractor to lower radon levels in an existing home is about $1,200, although the repairs may range from $500 to $2,500 (U.S. EPA 1993). Operating costs add an additional $75-175 annual expense, and heating and cooling bills may also be increased.

The earlier years of radon mitigation focused on depressurization techniques; the most common system now in use, active soil depressurization (ASD), draws air from beneath the slab to create a slight negative pressure underneath the structure ("sub-slab suction"). Creating a pressure differential large enough to lower radon below the EPA guideline often requires drilling several holes into the concrete slab and installing associated piping and forced-draft fans to vent the air above the roof (Freije 1990). The floor slab must be nearly air tight so that collection efforts are not short-circuited and excessive indoor air pulled down through the slab and up into the system (Christian 1991). This can result in added basement depressurization, which may also worsen backdrafting.

Frost formation where warm air passes through cold air spaces has been found to block exhaust pipes; frozen and poorly drained soils have been found to obstruct sub-slab airflow. The EPA has published numerous guides for ASD design and is expected to monitor its use more closely. Due to the lack of information on long-term effects of ASD on soil beneath the foundation and the possible presence of methane or other soil gases, the EPA has recommended requiring soil engineers test soil composition and permeability (U.S. EPA 1994). Still, ASD is currently the most documented, prevailing radon mitigation technique.

Due to the danger involved in backdrafting of combustion appliances and increased concern about overall IAQ, more radon mitigation systems are incorporating some form of fresh-air intake and ventilation. Low cost options are naturally ventilating or pressurizing the basement/crawl space with supply-air fans, although this may add substantial heating/cooling loads or make spaces unlivable. Natural basement ventilation has been shown to be an effective radon measure in houses containing radon levels less than 10 pCi/L (Du Pont and Morrill 1989).

While it has received scant attention in the radon mitigation literature, basement pressurization is thought to have the capability to provide significant radon reduction in "tight" homes. A positive pressure shield prevents radon gas from entering a building and causes air to flow out through cracks and holes in the basement into the soil. It can also simultaneously reduce radon and other indoor air pollutants through dilution with fresh air supplied by the blower. Basement pressurization can be achieved by sealing return ductwork of a building's central heating system and creating an outdoor air supply; testing has shown the method to be as effective as ASD in controlling indoor radon levels. Its largest drawback is the energy penalty of increased air infiltration, and long term data has not been published on its energy costs, effectiveness, reliability or possible structural effects (Renken and Konopacki 1993).

Heat recovery ventilation (HRV), which transfers heat from exhaust indoor air to fresh outdoor air, is another common approach to improve IAQ with less energy loss. HRVs have been found to be practical for radon mitigation in houses with low to radon moderate radon levels. A study of balanced HRVs concluded that radon could be reduced below the EPA guideline through simple dilution (Nazaroff et al. 1991); another study reported the same method could reduce radon levels by about a factor of six (Holub et al. 1985).

In self-enclosed air-to-air heat exchangers (AAHX), 60-80% of household heat may be retained. While expensive to purchase commercially, such a system may be fairly easily constructed for a few hundred dollars (Shurcliff 1982). However, installation requires care to ensure intake and exhaust flow streams are balanced; improper balancing causes many units to remove more air from the house than they supply, which depressurizes the indoors and thus increases radon infiltration and backdrafting potential. Maintenance is also critical; air flow rates are reduced and AAHX effectiveness deteriorates if dust and particulates plug the filters and sections of the core. HRVs can be set to pressurize indoors by removing less indoor air, but heat recovery efficiency is reduced.

A study of 366 homes with AAHX found that some occupants experienced noise problems with vibrations or fan hums, unpleasant drafts, condensation, and core freezing

(Vine 1987). AAHX use was found to be bimodal: 42% used it for 1-4 hours per day, and 30% used it for more than 18 hours a day; 5% of the owners reported they had never used their heat exchanger. A year after installation 40% of the households reported that they had not changed the filter. Despite protection systems, about 10% reported freezing of their AAHX core and obstruction of air flow due to condensed water from cooling of the warm outgoing airstream.

The "exhaust air heat pump" is another type of HRV that combines ventilation, water heating, and partial space heating/cooling by drawing air from kitchen and bathroom vents and recovering/removing thermal energy in a water storage tank. The exhaust air is then vented outside; when the water reaches a set temperature, it is circulated through the house. While the technique can provide ventilation throughout the year, it also increases radon infiltration and backdrafting potential through depressurization.

Thus, conventional radon mitigation systems have drawbacks in high installation costs, depressurization potential, and/or energy penalties. As elevated radon levels and other indoor air pollutants increase during the heating season due to more tightly closed structures, the stack effect, and operation of combustion appliances, the demand for radon reduction and indoor air quality improvement methods which provide positive pressurization and energy savings is also increased. Little research on systems addressing both depressurization and energy costs is documented in the literature, although a few innovative designs are under development.

Secondary Heat Recovery and Radon Reduction

A combined radon mitigation and energy conservation retrofit system utilizing a heat exchanger to recover heat normally lost through furnace flue exhaust has been field tested on two homes in Wisconsin (Renken and Konopacki, 1993; Renken and Coursin 1994). With this Basement Pressurization-Heat Recovery System (BP-HRS), exhaust flue gas was passed through a secondary heat exchanger and vented outdoors while 300 CFM of fresh air was warmed and discharged into the basement; the unmixed air streams were distributed through copper tubes arranged in counter-flow orientation. A backdraft damper on the outlet end of the flue pipe was added to prevent outdoor air from dispersing combustion products indoors; a flexible damper at the fresh air outlet obstructed back flow of air outdoors.

In the two test homes, BP-HRS operation achieved positive basement pressure relative to the surrounding soil pressure, heated ventilation air, and reduced furnace operation. Although a vacuum switch safety feature does not allow the furnace to operate if the exhaust blower fails, monitoring during operation revealed an overall increase in basement carbon dioxide levels up to 1500 ppm. While this amount is relatively small and no detectible carbon monoxide was present, it signals possible drawbacks in the strategy.

Year-round BP-HRS ventilation was initially allowed by a timer connected to the blower thermostat; when the furnace is not in use and the outdoor temperature reaches 13°C or above, the timer triggers the outside air handler and provides cyclic basement pressurization without heat recovery. Such intermittent operation was found to be sufficient to prevent radon gas entry due to sustained displacement. Scintillation cell continuous radon monitor measurements at one test house indicated that indoor radon levels returned to 4 pCi/L following a one hour delay after the air handler turned off; fan operation for ten minutes out of every hour was found to reduce the concentration to about 1 pCi/L. The researchers noted that because every house has a characteristic radon migration rate, the required cycling time for air handler operation will vary accordingly (Renken and Konopacki 1993).

In the second installation, the BP-HRS was tested with a variable speed blower delivering mixtures of makeup air from both outdoors and the upstairs. It was found to actively reduce indoor radon levels of more than 35 pCi/L by an average of 83%, and as much as 97% without a severe energy penalty. Commercial installation including weather-stripping and caulking was predicted to cost about $1150.

During the heating season, the cost to operate the system's blowers is offset by the savings in heating fuel, and summer operation results in an estimated $25 in extra cooling costs. The ability to draw air from the first floor prevented the system from lowering basement temperatures on extremely cold days; however the circulation of radon-laden indoor air reduced mitigation effectiveness. Relative humidity remained stable at about 45% for the duration of testing, alleviating concerns of possible mold formation due to the introduction of outdoor air.

The same study also characterized environmental influences on indoor radon entry and egression including pressure differentials, precipitation, soil and outdoor temperatures, barometric pressure, wind velocity and direction, humidity, and solar insolation. PC-based acquisition of field data enabled the documentation of relationships between specific meteorological conditions and radon gas entry. Radon levels in residential structures have been thought to follow a diurnal pattern, and this study determined that on most days registering strong sunlight, the radon level peak occurred a small time delay after the solar radiation climax. Radon levels and solar radiation may have several links since sunlight affects temperature, wind, barometric pressure, and home heating requirements. Indoor radon was also found to have noticeable relationships with precipitation and natural ventilation rate, which itself is driven by both wind speed and the temperature difference between inside and outdoor air. Precipitation was associated with an elevation of radon levels by an average of 30%, although a delay of up to four hours between the onset of precipitation and the initial rise in radon was observed. An expected inverse relationship between barometric pressure and radon level was seen, even during periods of no precipitation, and the pressure communicated relatively quickly through the building. Thus a decrease in barometric pressure allows soil gas to migrate into the house at a higher rate, increasing the indoor radon level, whereas a rise in pressure retards soil gas movement and lowers indoor radon.

Solar Energy

Solar radiation arrives at the surface of the earth at an average rate of 180 watts per square meter and varies primarily as a function of latitude. The traditional solar collector is a large panel with glass or plastic "glazing" placed over a blackened collecting surface, which traps a layer of air and reduces conduction heat loss. Incoming solar rays are converted to thermal energy, and warmed air flows passively or is pumped indoors. Nearly all solar air heaters in the literature are configured in closed loop circulation, with indoor air vented through the panel and returned into the house. Such systems are usually coupled with conventional heaters and are controlled by thermostats, valves, or timers to permit the most efficient use of solar and conventional energy (Reif 1981).

At the average rate of solar energy arriving at the earth's surface with a typically 50% efficient recirculating air solar collector, the daily energy output per square meter is roughly equivalent to burning 1/10 gallon of heating oil in a 70% efficient furnace (Craig 1988). However, once-through solar heating, which draws in outdoor air, may use solar energy more efficiently than recirculating indoor air, because the rate of heat transfer from the solar panel to the air is greater with colder intake air (Kutscher et al. 1991).

Although the greatest building heating needs often occur when available sunlight is least, thermal storage and the use of solar energy for domestic and commercial hot water can reduce this disadvantage. Water circulating through tubes on the collecting surface can serve as a heat transfer fluid, and the heat is exchanged to a storage water tank. Even in cool temperate climates with considerable cloudiness solar energy can provide 50% of domestic heat in most areas. Such systems are not more widely used because conventional sources of energy are still fairly cheaply available, and while they are not technically complex and operating costs are negligible, the initial cost of installing solar systems has been considered high.

Solar Ventilation Air Preheating

The National Renewable Energy Lab (NREL) has tested a new "unglazed transpired solar collector," intended for preheating ventilation air at large manufacturing buildings, which may be the most efficient active solar heating system ever designed (Kutscher 1992). Conserval of Toronto, Ontario, has installed such a collector with the commercial name Solarwall on two industrial buildings in Canada. The collector consists of black-coated perforated (transpired) aluminum without glass or plastic glazing and typically covers the south side of a building (up to 5500 m^2 of collector area). A fan draws fresh air through the perforations, warmed 10-15°C above outdoor temperatures, and delivers it 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. The system includes no explicit solar heat storage, but some heat is stored in the building mass.

Based on the difference between collector temperature and outlet airstream temperature, the Unglazed Ventilation Air Preheat (UVAP) system transfers solar heat to the ventilation airstream with an average efficiency of 50-60%.

At about \$90/m^2 (\$10 per square foot), UVAPs have been found to be cost effective for large commercial buildings in colder climates. Other applications include crop drying, desiccant materials regeneration and radiant cooling.

A 27.9 m^2 (300 square foot) Solarwall installed on NREL's Waste Handling Facility in Golden, Colorado, has proven to be a substantial supplemental heat source and an "ideal" solar application. Because the building is used to store chemical wastes, very high ventilation rates of 1.4 m^3/s (3000 CFM) and electrical heating are required, resulting in a considerable building heating costs which the UVAP partially offsets. Coupled with Colorado's solar resource, this results in a predicted pay-back of just three years (Kutscher 1992).

Compared to the SRRS using 3 m^2 (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. An NREL model of a 9 m^2 unglazed transpired collector showed that with an incident solar insolation of 700 W/m^2, a suction velocity of 0.05 m/s, and an ambient temperature of 10°C, the predicted temperature gain for air delivered at 45 cm^3/s (950 CFM) is about 12°C. SRRS forced-draft intake of 3.5 cm^3/s with a 3 m^2 panel would correspond to suction velocity at 0.01 m/s, and the results presented in Chapter 6 compare favorably to theoretical estimates of UVAP performance at this flow rate. NREL research is currently exploring the limits of collector size and delivered temperatures appropriate for unglazed transpiration.

While research has not been conducted with the UVAP system in respect to radon mitigation, it would likely result in a slight pressurization indoors and thereby reduce radon infiltration. Since all commercially available ventilation/pressurization radon mitigation systems, including those equipped with heat recovery devices, operate at a net energy loss due to heating and electrical demands, the time is ripe for solar energy to be utilized by the radon industry (Klein and Olson 1993).

IV PROJECT HISTORY

This chapter documents events leading up to the current investigation: the design of the SRRS as a new configuration for solar air heaters; the development of a "do-it-yourself" guide and attention generated by the strategy; and previous research conducted on two homes. In order to uncover further research needs, earlier data is reviewed and findings are reanalyzed; the lack of a control for weather effects and other time-dependent external factors is identified. As reported by Klein and Olson (1993, 1994) and Rhoads et al. (1995), the SRRS is 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 costs, and homeowners expressed satisfaction with improved general indoor comfort.

SRRS effectiveness was directly related to the duration and volume of air delivered at an airtight home, but less correlation was seen at a leakier house. Several possible system configurations and operational modes were investigated, and a timer-based schedule was developed to maintain first floor radon below the EPA guideline. Direct basement discharge of SRRS outlet air was determined to be preferable to distribution into living areas, as it rendered the introduction of under-heated air less noticeable to occupants and achieved an apparent stronger mitigation. SRRS summertime effectiveness was also clearly demonstrated, and energy costs and savings were estimated.

SRRS Design

Seeking to address both elevated radon levels and heating costs, HVAC specialist Richard J. Klein devised an original solar ventilation system to introduce fresh, pre-heated air indoors in 1990 at his home in Waterloo, Iowa (pictured in Appendix A). Comprised of a 4' × 8' flat-plate solar air collector, ductwork into the central heating system, a mechanical blower, thermostat, and simple electrical circuitry, the Solar Radon Reduction System (SRRS) was designed to improve air quality in an energy-efficient manner (Fig. 3).

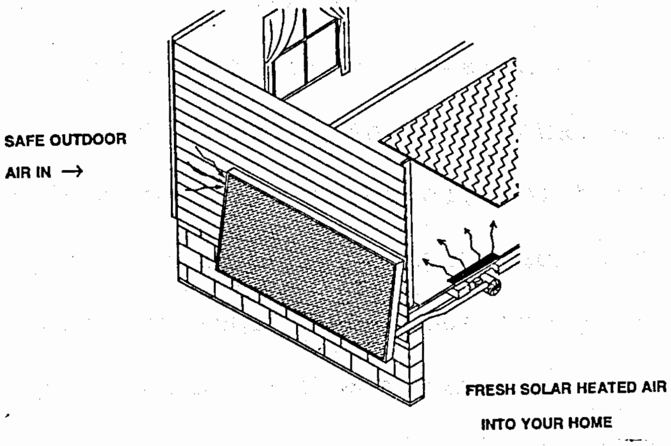

Figure 3. Diagram of the Solar Radon Reduction System (Klein 1993)

The SRRS helps to lower indoor radon levels through reduced infiltration and dilution by delivering a supply of outdoor make-up air for combustion appliances and stack effect losses. During cold seasons, the SRRS introduces solar-heated outdoor air indoors, augmenting the existing heating system for a net energy gain. In the summer months, the system's blower provides low-energy cooling by ventilating the structure when outdoor air temperatures drop below indoor comfort levels. The amount of fresh air provided by the system is dependent on the number and capacity of solar panels and fans installed, allowing flexibility for use in residential, commercial, and manufacturing facility settings.

Based on charcoal canister tests, the SRRS reduced Klein's winter basement radon level more than 70%, from 8.8 to 2.5 pCi/L (Klein and Olson 1993). In 1991 the system received an EPA Innovative Radon Mitigation Design award, and the EPA requested further research according to EPA protocols (U.S. EPA 1986). An additional solar collector constructed from recycled materials which heats water as well as air was installed in conjunction with the first SRRS to extend energy savings throughout the year (Appendix A).

A second complete SRRS was installed in 1991 at a test home in Cedar Falls, Iowa, which exhibited an unmitigated spring-time basement charcoal canister radon reading of 19.9 pCi/L (Appendix A). Together with the fan, wiring, and ductwork, SRRS construction costs were estimated to be $200, about 10% of comparable commercial mitigation systems (Klein and Olson 1993). In 1993, the SRRS design was issued U.S. Patent 5,186,160 (Appendix B) and awarded research funds by the University of Northern Iowa's Reuse and Recycling Technology Transfer Center. A detailed instruction manual was developed for homeowners or contractors describing how to custom-build a complete SRRS including the solar panel, and install it on a south-facing wall, roof, or as free-standing unit (Klein 1993).

Initial Evaluations

SRRS efficiency evaluations were first conducted in the winter of 1992-93 at test home North, a 960 ft^2, 1½-story wood-frame home equipped with a natural gas water heater, clothes dryer and forced-draft furnace; and test home Lovejoy, a single story, 1270 ft^2 wood-frame home with all-electric appliances including a forced-draft furnace. Radon levels were measured as the mean of 4-hour intervals with continuous radon dataloggers (Honeywell Model 05-418) operated in accordance with EPA protocol (U.S. EPA 1993). Blower door tests were conducted to determine natural infiltration rates, and basement pressures were determined with manometers. One SRRS fan at North produced an air flow of 65 CFM, delivering 0.6 additional air changes per hour (ACH); Lovejoy's SRRS produced 75 CFM, adding 0.4 ACH. The duration of SRRS and furnace operation were measured with elapsed time hour meters; temperature/ relative humidity strip recorders and weather data were used to calculate energy usage (Klein and Olson 1993).

Operated side-by-side at Lovejoy, the two Honeywell monitors were determined to be calibrated within 96% confidence based on ten-day means of 8.4 and 8.3 pCi/L and a carbon canister result of 8.1 pCi/L. The initial evaluation was conducted with "solar-trigger" operation, 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 indoor comfort levels, to a minimum of 25°C and often as high as 50°C.

Compared to closed house radon levels, SRRS solar operation was found to lower first floor mid-day radon levels by an average of 29% at North and by 24% at Lovejoy, even though cloudiness limited operation to less than one hour on 15 of the 42 days (Fig. 4). Due to continued radon infiltration when the fans were off, night-time and early morning radon levels returned to near closed house levels.

The second mode evaluated the effect of the SRRS operating for additional periods, when the home required furnace heating, as well as during solar insolation. In this "solar/furnace-trigger" mode, SRRS fans were wired to activate based on both the solar thermostat and an electrical relay from the central furnace. In addition to allowing longer operation, this mode provided ventilation at intervals throughout the day and night.

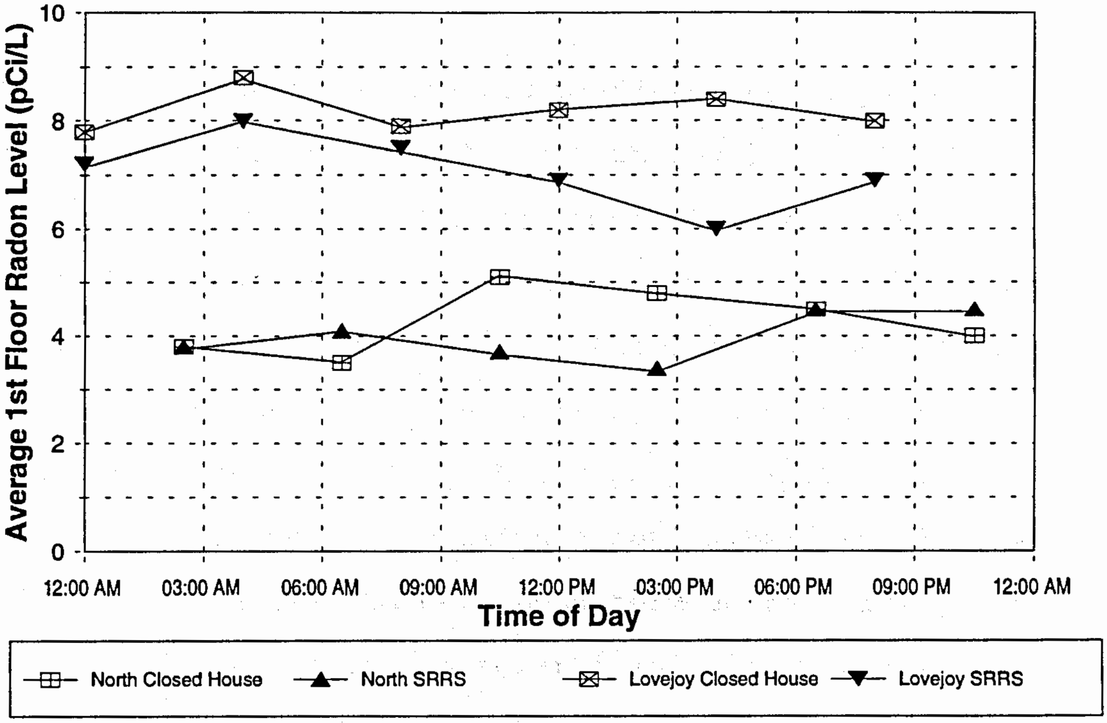

Figure 4. SRRS solar-trigger operation at North and Lovejoy, January-March 1993

Extended solar/furnace SRRS operation accomplished maximum radon reductions of 53% at North and 56% at Lovejoy compared to closed house levels. As a ventilation/ pressurization mitigation system, SRRS effectiveness was expected to be related to the duration and volume of air introduced into the dwelling. Data collected during extended operation showed mixed results: reduced radon was directly correlated to duration of system operation at Lovejoy (Fig. 5); yet North showed little correlation (see Klein and Olson 1993), which may be attributed to dwelling leakiness as discussed in Chapter 7. Based on linear regression of the data obtained, SRRS operation (with 75 CFM fan flow) 12 hours per day was predicted to keep Lovejoy's first floor radon below EPA's action level of 4.0 pCi/L.

Even in this solar/furnace-trigger mode the SRRS provided substantial energy benefits by delivering solar-heated air several hours a 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, verifying that the SRRS yielded a net, albeit small, energy savings in both test homes. Long-term energy savings were predicted to be greater as solar insolation received during the period was about half that typically available in the region (Klein and Olson 1993).

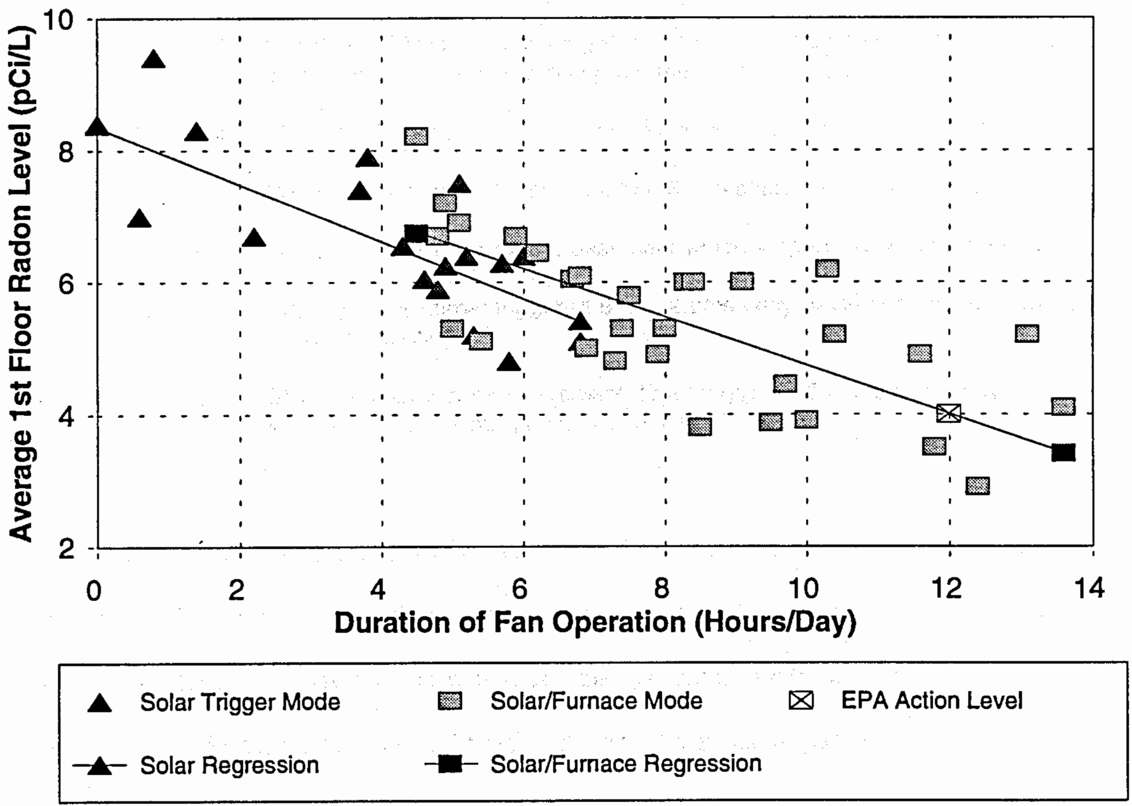

Figure 5. Effect of solar-trigger and solar/furnace SRRS operation at Lovejoy (Klein and Olson 1993)

Modification and Evaluation

Further testing continued in 1993-94 to evaluate other possible SRRS modes as well as to determine the optimal configuration and resulting radon reduction efficiencies (Klein and Olson 1994). Equipped with both Honeywell monitors, Lovejoy was monitored over seven months with added mitigation methods as shown in Table 2, selected to coincide with EPA's recommended action steps (U.S. EPA 1986).

Table 2. Increased Radon Mitigation Steps at Lovejoy

Period	Time Interval	SRRS/Dwelling Conditions
1	9/10-10/7/93	SRRS deactivated; periodic open house conditions, basement windows open.
2	10/8-11/8/93	SRRS deactivated; closed house conditions.
3	11/9-11/26/93	SRRS 75 CFM fan discharging through central heating system to 1st floor with solar-trigger mode; sump pump pit sealed, passively vented outdoors.
4	11/27-12/29/93	SRRS 1st floor solar mode; sump pit vented outdoors with 45 CFM fan.
5	1/1-1/9/94	SRRS 1st floor timer-triggered 2 hrs, 3 times/day; sump pit forced venting.
6	1/10-2/6/94	SRRS 1st floor solar mode; basement window open, sump pit forced venting.
7	2/7-2/22/94	SRRS 1st floor timer-triggered 6 hrs, 2 times/day; basement window open, sump pit forced venting.
8	3/25-4/17/94	SRRS discharging into basement, timer-triggered 6 hrs, 2 times/day; basement window closed; sump pit forced venting.

Data collected indicates incremental reductions for each of the test configurations (Fig. 6). The first mode, with the SRRS deactivated and basement and upstairs windows open periodically, resulted in an average basement radon level of 3.2 pCi/L, which represents the minimum attainable level utilizing natural ventilation as the sole mitigation strategy. While this simple method achieved low radon levels, such open house conditions are impractical in Iowa and most temperate climates several months of the year.

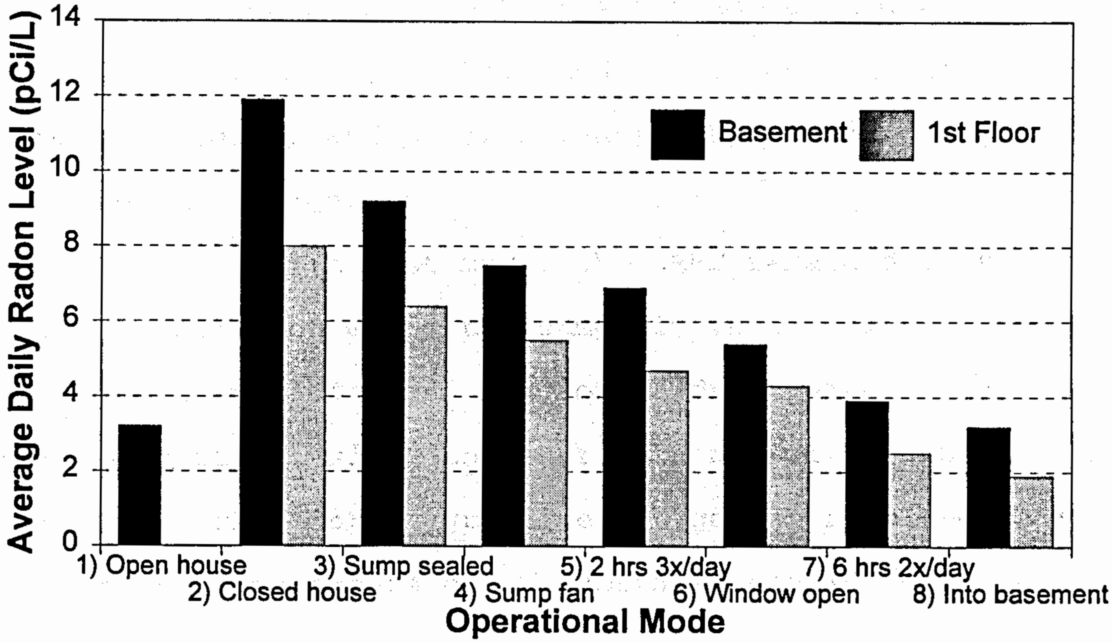

Figure 6. Incremental radon reduction at Lovejoy

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 radon reduction efficiencies for subsequent SRRS test modes. Lovejoy had a visually sound basement concrete slab and foundation walls, but an open foundation drain tile sump pit was identified as a possible direct radon entry point.

During the third test period, the SRRS was activated to discharge air through the home's ductwork into the first floor living area with solar-trigger operation. In addition, the foundation drain tile sump pump pit was sealed and passively vented to the outdoors, lowering radon levels an average 20% upstairs and 23% downstairs. These values are similar to first year solar-trigger tests showing a 24% reduction, suggesting the mitigation achieved during this period was primarily due to SRRS operation; in this case sump pit sealing and passive venting appeared to negligibly improve the mitigation.

In the fourth test mode, the SRRS remained in solar-trigger operation while the sump pit ventilation system was modified to include a 45 CFM forced-draft exhaust fan, a variation of sub-slab depressurization. Given constant SRRS operation, this more aggressive mitigation resulted in radon reduction improvements of 11% upstairs and 14% downstairs over test period 3.

During optimum solar insolation conditions (i.e. non-cloudy days), the SRRS operates for approximately 6 hours, typically between 9 am and 3 pm. To evaluate uniform SRRS operation compared to weather-related operation, a timer was set to activate the fan for two-hour intervals spaced three times throughout the day. Based on data obtained during the fifth test mode, SRRS radon reduction during actual solar-driven operation was estimated to be 90% of that measured under timer-based operation. The researchers attributed this high actual to ideal efficiency to the system's delivery of low impedance appliance make-up air regardless of fan operation, reducing stack-driven negative basement pressures throughout the day (Klein and Olson 1994).

Since basement radon remained consistently higher than first floor levels, increased air supplied directly to the basement was added to the mitigation in test period 6. Natural basement ventilation (one basement window open) incorporated with SRRS solar-trigger operation was found to again lower radon levels; the relative difference between basement and first floor levels was reduced.

In consideration of results from first year testing which indicated that 12 hours of SRRS operation could achieve an average 4.0 pCi/L upstairs, for test mode 7 the timer was set to activate the fan 6 hours twice a day. One of these periods coincided with the optimum solar insolation period (9 am to 3 pm) to obtain maximum energy gain and the other provided evenly-spaced mitigation during the night; radon levels were reduced an average of 68%.

In test period 8, the basement window was closed and the SRRS was modified to discharge directly into the downstairs rather than through the home's central heating system to increase basement pressurization. With the fan still timer-activated 12 hours/day, this approach achieved the maximum reductions, of 76% upstairs and 73% downstairs.

While significant radon reductions were demonstrated with these increased mitigation steps, the data acquired sequentially expressed a monotonic trend and did not exclude the possibility of systemic errors such as baseline shifts or external influences. Weather conditions varied widely through the periods, from mild fall temperatures during the first periods through the coldest part of the winter (periods 5-7) and then into the warmer spring during period 8. Because the home was occupied during testing, the first floor was likely less "closed" during warm weather, which may have aided the mitigation during those periods; basing reduction efficiencies on the fall closed house baseline may also introduce errors.

Long-Term Evaluation

Further evaluations of 12-hour timer-based SRRS operation were continued at Lovejoy through the summer of 1994 to evaluate the effect of both the SRRS intake fan and the sump pit exhaust fan (Rhoads et al. 1995). The three-month basement radon levels from May to July with both fans operating averaged 3.9 pCi/L (Fig. 7). For a two-week period in July, both fans were deactivated and the house was maintained in complete closed house conditions (no ventilation) while the homeowners were on vacation; the basement quickly returned to high radon levels. This closed house average of 17.7 pCi/L is substantially higher (49%) than the 11.9 pCi/L baseline obtained the previous fall, further suggesting the possibility of baseline shifts/external factors.

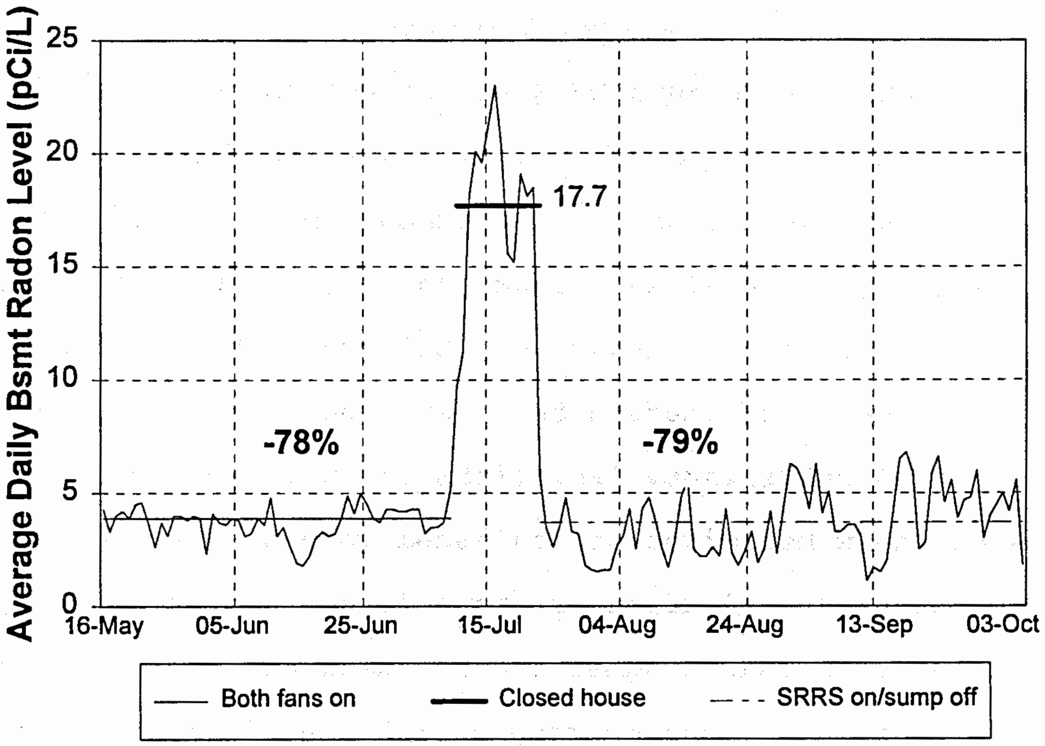

Figure 7. Relative importance of SRRS and sump pit fan operation on radon mitigation

The following three months with only the SRRS fan operating showed larger daily radon fluctuations but a long-term average almost equivalent to the test with both the SRRS and sump fans (3.7 pCi/L). This data verifies summertime SRRS performance and demonstrates the stronger mitigation influence of SRRS ventilation and positive pressurization relative to the sub-slab suction achieved by the sump fan, although energy costs were not monitored and the sump fan was not tested alone. It also indicates that the lowest expected long-term basement radon levels at Lovejoy even with combined mitigation methods are in the 4 pCi/L (75%) range.

Energy Benefits

A major advantage of the SRRS over other radon mitigation methods is the introduction of solar-heated air indoors during cold seasons as well as summertime cooling. Even in extended operation, SRRS uses less energy costs than both sub-slab depressurization systems, which introduce no external air into the house, and systems that require conventional heating for additional ventilation air supplied. SRRS energy benefits are optimized when operation is limited to periods of adequate solar isolation during the heating season and when outdoor temperatures drop below ambient indoor levels during warm weather. In other modes the SRRS may introduce under-heated air during cloudy days and nighttime winter operation, as well as overly warm and humid outdoor air during the cooling season.

Such heat gains and losses were estimated for 12-hour timer-based operation (6 hours twice/day) at Lovejoy based on outdoor and indoor temperatures, the SRRS fan flow rate, house air change rate, and conventional energy costs for the month of March 1994. Energy delivered by the solar panel was calculated with the standard psychrometric formula:

$$\text{BTU} = \text{specific heat of air} \times \text{mass} \times (T_{\text{inlet}} - T_{\text{outlet}}).$$

For during periods lacking adequate solar insolation, heat loss caused by cold air delivery was calculated as:

$$\text{BTU} = \text{specific heat of air} \times \text{mass of indoor air} \times \text{ACH} \times \text{hours of unheated fan operation/day} \times \text{HDD}.$$

Net energy costs were determined by subtracting heat loss and electricity used from heat gain. Outdoor temperatures for the period averaged 2°C, and temperature strip-recorder monitoring indicated that SRRS outlet air averaged 10°C based on delivery at:

--38°C for 4 hours, 20°C for 2 hours on 10 clear days;

--20°C for 6 hours on 11 partly cloudy days;

--2°C for 6 hours on 10 cloudy days; and

--2°C for all 31 6-hour nighttime operation intervals.

The net energy content of SRRS supplied air was therefore calculated to be 1.7 MBTU for the month, and the enthalpy of indoor air at an average 22°C replaced by SRRS air was estimated at 2.7 MBTU (Klein and Olson 1994). Thus approximately 1.0 MBTU of extra heating energy (300 KWH with an electric furnace) was required to accommodate SRRS outlet air for the entire month. The 115 Volt, 0.59 amp induced-draft fan operating 12 hours/day for 31 days used 25 KWH of electricity. At the Cedar Falls, IA volume-discounted rate of $0.03/KWH, the net energy expense attributable to SRRS operation for March 1994 was about $9.75 (31¢/day). The solar collector's heat input saved 510 KWH or $15.30 (49¢/day) over direct introduction of outdoor air.

If each month of operation resulted a similar demand on either heating or air conditioning, the annual SRRS operating bill would be around $117. Compared to sub-slab mitigation systems, which do not introduce ventilation air indoors and typically cost $2,500, contractor installation of the SRRS was estimated to cost $500. Using a similar fan 24 hours/day, sub-slab depressurization would require 50 KWH/month or $42/year and possibly add heating costs. Ignoring the time value of money, energy payback toward the sub-slab system would be about 27 years, indicating that even with extended operation the SRRS may be economical.

A separate investigation comparing the SRRS solar intake design to a recirculating solar air system found that the temperature of outlet air is only slightly less when cold outdoor air is used than when room-temperature indoor air is reheated. Thus collector efficiency in utilizing incoming solar energy appears to be increased by heating the colder air, which can be used to dilute polluted indoor air (Rhoads et al. 1995).

Further Questions Raised

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. As radon reductions and energy savings were expected to vary in further installations, more precise examination of factors affecting SRRS use was desired.

For example, the influence of house characteristics such as size and airtightness on mitigation efficiency was not known, nor was SRRS pressurization quantified. More comprehensive monitoring of SRRS and environmental parameters could provide a better picture of heat gain and weather effects, and a radon control would be needed to enable comparisons between houses. Finally, more efficient operational modes to maximize SRRS radon reduction and energy benefits at a range of houses could be developed. A high success rate of achieving EPA's radon action level and net energy gains would substantiate SRRS viability and increase competitiveness with standard mitigation practices.

V MATERIALS AND METHODS

This chapter provides site descriptions of the test homes studied and an overview of methodology, experimental design, and instrumentation used. After installing SRRS and measurement equipment at the five test sites and a "control" house, radon levels and other environmental parameters were recorded during closed house conditions and various SRRS operational modes to determine radon reduction effectiveness and energy benefits. Testing of SRRS design improvements and operational modes was intended to quantify radon reduction with varying energy use/gain as well as to determine optimal system configuration, the best balance of energy benefits and radon reduction needs, for each house.

Characterization of Test Sites

Volunteer test subjects who would accept SRRS installations were recruited, and ten potential homes were screened for radon and solar applicability in the spring of 1994. The investigation included six houses in Waterloo and Cedar Falls, Iowa, due to availability of computer acquisition equipment and low-cost radon monitors: one of the SRRS homes used in the previous research (referenced as Lovejoy for its street name); four new test houses (Byron, Sager, Vermont, and Washington); and a sixth house (Control, also located on Washington Street) to serve as a "control" for radon levels. The research plan was approved by the

University Review Board for Research on Human Subjects, and the volunteers signed informed consent forms (Appendix C).

The homes selected were moderately sized and as similar as possible to serve as replicates. Initial summertime closed house testing indicated that Lovejoy and Sager could serve as "high" radon sites (15-20 pCi/L); Byron and Vermont would be "moderate" radon sites (8-10 pCi/L); and Washington and Control would be "low" radon sites (4-6 pCi/L). As it turned out, during the later December closed house testing, Vermont exhibited much higher radon levels (19 pCi/L) even than Sager, effectively switching their rank. Such uncontrollable external variables, as are expected with field tests, were the main reason the experimental design included a control and monitoring of numerous parameters.

Airtightness of Houses

Since house air exchange rates can greatly affect both radon levels and mitigation efficiency, Minneapolis Blower Door Tests were conducted at each site to characterize leakiness. Consisting of a variable-speed 6000 CFM fan sealed into an exterior doorway, the blower door creates pronounced negative pressure indoors relative to outdoors; pressure differentials measured at various fan flow rates are used to estimate natural infiltration. Measurements are taken with the house under constant pressures significantly greater than those normally applied by wind and convection forces to minimize variations (Energy Conservatory 1994).

The flow needed to create 50 pascal (Pa) pressure differential (CFM_{50}) is the most common blower door measurement, typically 500-8000 CFM.[4] Since fan pressures approximate air flow entering the house through cracks and holes, fan flows are corrected for differences in air density based on temperature, which can affect results up to 5% in extreme weather conditions. Data taken over a range of house pressures allows estimation of air flows too low to measure accurately. Such multi-point tests include several readings between 20-60 Pa to provide a "house leakage curve"; natural infiltration rates can then be estimated with leakage models, described below, based on flow rates determined with this curve (Energy Conservatory 1993).

Information obtained from blower door tests on the houses for this study is listed in Table 3. Tests at Control, Byron, and Sager were conducted on October 14, 1994, and tests at Lovejoy, Vermont and Washington were conducted on November 11, 1994; the National Weather Service reported both days had variable winds of 5-10 mph. Each house's dimensions were measured, the above-grade surface area and volume including the basement were calculated, and indoor and outdoor air temperatures were measured.

[4] For very leaky houses, 50 Pa often cannot be generated even with the fan operating at full speed, so CFM_{50} is estimated based on the flow required for the highest achievable house pressure.

Table 3. Blower Door Test Results

	Control				Byron				Lovejoy			
Envelope Area	2829 ft2				2931 ft2				4344 ft2			
Volume	18150 ft3				13474ft3				21184 ft3			
Heated Stories	2.0				2.0				1.0			
Temperature In/Out			63F	62F			71F	60F			69F	48F
Pressure Data	Ph	Pf	CFM	% Err	Ph	Pf	CFM	% Err	Ph	Pf	CFM	% Err
	33	68	3945	0	17	6	1176	0	73	62	1364	-0
	29	55	3552	-1	23	8	1356	-2	63	55	1286	2
	23	41	3072	0	33	13	1724	1	56	42	1125	-2
	19	32	2718	1	40	16	1911	1	46	33	998	-1
	15	22	2258	-1	47	18	2025	-1	38	27	904	1
Correlation Coefficient				0.998				0.995				0.990
C & n Factors			353.73	0.688			245.80	0.552			79.63	0.664
House Pressure		4Pa	10 Pa	50 Pa		4Pa	10 Pa	50 Pa		4Pa	10 Pa	50 Pa
CFM		918	1726	5227		528	876	2130		199	367	1070
Standard Err %		3.5	1.8	1.3		6.3	3.7	1.4		15	9.6	1.4
Effective Leakage Area	260.43 sq in				149.79 sq in				56.69 sq in			
Equivalent Leakage Area	506.95 sq in				257.33 sq in				107.93 sq in			
Mpls Leakage Ratio	1.84 CFM50/sq ft				0.72 CFM50/sq ft				0.24 CFM/sq ft			
Leakiness at 50 Pa	17.28 ACH50				9.48 ACH50				3.03 ACH50			
LBL N Factor	CFM50/13.5				CFM50/13.5				CFM50/17.0			
Average Natural Infiltration	385 CFM				156 CFM				62 CFM			
With 6 occupants	64.1 CFM/person				26.1 CFM/person				10.4 CFM/person			
Natural Air Change	1.273 ACH				0.699 ACH				0.178 ACH			
House Air Time Constant	0:47 Hrs/AC				1:25 Hrs/AC				5:37 Hrs/AC			

	Sager				Vermont				Washington			
Envelope Area	2690 ft2				2546 ft2				3344ft2			
Volume	13232 ft3				11655 ft3				18425ft3			
Heated Stories	1.0				1.0				2.0			
Temperature In/Out			68F	55F			69F	58F			63F	42F
Pressure Data	Ph	Pf	CFM	% Err	Ph	Pf	CFM	% Err	Ph	Pf	CFM	% Err
	19	6	1174	0	53	83	1592	-0	52	34	2746	0
	23	7	1267	1	47	73	1494	-0	47	29	2538	-1
	31	8	1353	-2	42	68	1442	1	43	27	2450	0
	42	10	1511	-2	37	60	1355	0	39	24	2311	0
	46	12	1654	2	34	53	1275	-1	37	22	2214	-0
Correlation Coefficient				0.979				0.993				0.994
C & n Factors			399.59	0.363			243.36	0.473			251.42	0.603
House Pressure		4Pa	10 Pa	50 Pa		4Pa	10 Pa	50 Pa		4Pa	10 Pa	50 Pa
CFM		661	922	1655		469	723	1549		580	1009	2669
Standard Err %		9.1	5.3	2.2		7.4	4.5	0.6		8.4	5.2	0.6
Effective Leakage Area	187.48 sq in				132.96 sq in				164.63 sq in			
Equivalent Leakage Area	270.96 sq in				212.50 sq in				296.58 sq in			
Mpls Leakage Ratio	0.61 CFM50/sq ft				0.60 CFM50/sq ft				0.79 CFM50/sq ft			
Leakiness at 50 Pa	7.50 ACH50				7.97 ACH50				8.69 ACH50			
LBL N Factor	CFM50/17.0				CFM50/17.0				CFM50/13.5			
Average Natural Infiltration	97 CFM				91 CFM				196 CFM			
With 6 occupants	16.2 CFM/person				15.1 CFM/person				32.7 CFM/person			
Natural Air Change	0.441 ACH				0.469 ACH				0.640 ACH			
House Air Time Constant	2:16 Hrs/AC				2:07 Hrs/AC				1:33 Hrs/AC			

The house measurements, temperatures, multiple pressure readings (Ph), and corresponding fan pressure readings (Pf) were entered into the Minneapolis Blower Door Computer Program which corrects for air density and calculates flow rates and infiltration models. Table 3 shows the difference between fan flows at each data point and the log-log linear regression curve (% Err); all of the tests for this study fall well within the required range for accuracy, ±2%. Correlation coefficients of the fit of data points to the curve are also listed; all were above the recommended 0.99 except Sager, which may have been affected by gusty wind.

C and n factors shown are empirically derived to determine house leakage curves; flows at 4, 10, and 50 Pa are used to calculate Effective Leakage Areas (ELA)[5], Equivalent Leakage Areas (EqLA)[6], and Minneapolis Leakage Ratios (MLR)[7], respectively, with standard errors shown for each based on fit to the house leakage curve. Wind over 10 mph affects estimates at low house pressures more than at

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[5] Used in a Lawrence Berkeley Laboratory model to estimate infiltration rates at typical house pressures, the ELA is defined as the area of a bell-mouthed nozzle (similar to the blower door fan inlet) which at 4 Pa has the same air flow as all the house's air leaks combined at 4 Pa.

[6] Defined by the National Research Council of Canada a round, sharp-edged orifice that leaks the same as the entire house at 10 Pa. Although actual house pressures are usually smaller, lower flow rates are difficult to calculate accurately even with multi-point tests.

[7] A method of adjusting leakage rates for house size used to assist weatherization; the CFM_{50} flow rate divided by above-grade surface area. Houses with MLRs above 1.0 can typically achieve large cost-effective reductions in infiltration with insulation and weatherstripping.

high pressures, and this error was always largest for 4 Pa for these tests, up to 15% at Lovejoy.

Calculated leakage areas reveal large differences between the houses in this study: ELAs range from 57 square inches at Lovejoy to 260 in^2 at Control, and EqLAs range from 108 in^2 at Lovejoy to 507 in^2 at Control. The test results shown were conducted with SRRS blowers deactivated; blower door tests also conducted with the SRRS fans operating indicated slightly larger leakage areas. A third test conducted at Sager with the SRRS outlet sealed indicated that the opening contributes about 4% of the house's leakage area during periods of non-operation. MLRs found for the test houses indicate that sealing efforts would be quite effective at reducing infiltration rates at Control but only moderately so at Washington, Byron, Sager, and Vermont; additional weatherization efforts at Lovejoy would not likely be economical.

To compare relative house airtightness, the CFM_{50} rate is often divided by house volume to determine air changes per hour at 50 Pa (ACH_{50}). For the six houses involved in this study, Lovejoy is by far the tightest, followed by Sager and Vermont, then Washington and Byron; Control is by far the leakiest, which may affect the value of its use as a control. These measures of house leakiness have particular implications for energy efficiency as well as for radon mitigation, which is discussed in Chapter 7.

Average natural infiltration rates (CFM_{nat}) were estimated with the LBL model which incorporate building characteristics of height, wind shielding, type of cracks, and the local climate (N factor). Both the extent of wind shielding and distribution of leaks were estimated to be normal for all test houses; the Energy Conservatory lists this region's climate factor as 17. Resultant average infiltration rates are divided by 6 to determine the amount of natural ventilation with high occupancy; natural air changes per hour (ACH_{nat}) are based on the natural infiltration estimates divided by house volume. Minimum levels of ventilation established by ASHRAE Standard 62-89 (15 CFM_{nat}/person or 0.35 ACH_{nat}) to maintain satisfactory indoor air quality are surpassed everywhere but Lovejoy, which indicates additional ventilation may be needed to prevent indoor air pollution there.

Finally, for further analysis of radon behavior in the test houses, time constants of air exchange were calculated as the inverse of ACH, hours per complete indoor-outdoor air exchange (H/AC), expressed in hours and minutes. As shown in Table 3, these values ranged from 47 minutes at Control to 5 hours 37 minutes at Lovejoy.

Appliances and Other Features

Additional house characteristics were recorded as potentially significant influences on radon behavior and overall indoor air quality (Table 4). 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 visually sound concrete slabs and foundation walls, although Sager and Lovejoy had experienced flooding during the previous record-rainfall summer.

Table 4. Test House Features

	Control	Byron	Lovejoy	Sager	Vermont	Washington
Year Built	1920s	1946	1960s	1954	1940	1910
Stack Height	3	1½	1	1	1½	2½
Occupants	2	1	3	2	1	2
Combustion sources	fireplace		wood stove, smoker		smoker	
Furnace	gas	gas	electric	gas	gas	gas
Water Heater	gas	gas	electric	gas	gas	gas
Clothes Dryer	gas	gas	electric	electric	none	none
Stove	gas	electric	electric	electric	gas	gas
Basement	full	full/heated	partial	full	full	full
Drain	open drain	open drain	vented sump pit	open sump pit	open drain	open drain
Foundation	stone	cement block	cement block	cement block	cement block	stone
Water-tightness	moist	seepage	flooding	flooding, mold	flooding	moist
Door	kept closed	none	kept open	none	none	kept closed
Use	storage	hobby	hobby	hobby	hobby	hobby
Exhaust Fans	none	kitchen/bathrm	bathroom	kitchen	none	none
Garage	detached	detached	attached	detached	detached	breezeway
A/C	window	central	central	central	window	central
Attic	full stairs	partial 2nd flr	climb up	climb up	climb up	climb up

The number and capacity of combustion appliances has a major effect on pressure forces due to their need for supply air and exhaust ducts/chimneys, and other factors such as clothes dryer and exhaust fan usage, garage and attic type, presence of sump/drain pits and fireplaces, and basement door/heating also affect house dynamics. Lovejoy was the only test home without natural gas appliances, although a wood-burning stove was present there (but rarely used). All garages were detached except at Lovejoy, although Washington's was connected by an unheated breezeway.

While all the homes had at least partially finished basements, none were currently used as living spaces. All had full basements (dimensions matching entire above-grade area) except Lovejoy, where a dirt crawl space was below a living room addition. Doors separating basements from living areas were present at Control, Washington, and Lovejoy, though none were tightly sealed and Lovejoy's was kept open. Vermont and Byron had heated basements with open vents, and Washington, Sager, and Lovejoy basements were partially heated through leaky supply ducts. Four of the houses had attics accessible by pull-down ladders; the Control had a full-staircase, third floor attic; and Byron's attic was on the second floor which also had a bedroom/office. All of the houses some air conditioning.

System Design and Installation

Installation followed the steps outlined in the SRRS instruction guide (Klein 1993) with modifications such as locating fresh air inlets below heated air outlets to take advantage of natural convection where possible. In addition, intakes near garages or other obvious air pollutant sources were avoided, and air cleaner filters were placed at both the inlets and outlets to reduce incoming particulates and outdoor allergens. As previous SRRS research indicated that direct basement discharge provided the most effective radon reduction and minimized resident discomfort during cold-weather operation (Klein and Olson 1994), all of the current sites used this configuration.

To optimize solar heating, panels were located to receive the most possible sunlight during winter and the best shielding from wind losses. Pictures of SRRS test house installations are shown in Appendix A. Aesthetics, house design, ease of cutting perimeter joists or basement windows, proximity to ductwork entry, and homeowners' desires also played major roles in mounting methods.

While collectors are best mounted facing solar south[8], an orientation of a few additional degrees west (in the northern hemisphere) can improve panel performance since atmospheric haze often reduces morning solar insolation available. The panels for this study were all mounted parallel to the houses' south-facing walls, within 15° of solar south, and flush when possible to maximize insulation and radiation escaping from the house. Sites that were

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[8] Indicated by the direction of shadows at local solar noon, exactly midway between sunrise and sunset; 6-7° west of magnetic south in northeast Iowa (Reif 1981). To accommodate site conditions, panels oriented 30° to either side of solar south can still receive 90% of the maximum solar radiation; even 45° deviations from solar south can attain 72% of radiation available during the heating season (Anderson 1991).

presumed to become the least shaded during the winter were chosen, although some shading at all sites was unavoidable.

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 collector performance can be greatly augmented by a horizontal reflecting surface such as snow cover[9] (Anderson 1991). Vertical mounting also reduces excess summertime radiation, which helps prevent panels from overheating.[10] Collectors installed at Byron and Sager were mounted vertically suspended on poles between 4" × 4" posts and can be tilted upwards during periods without snow cover. The top of Washington's panel was anchored to the house and the bottom was tilted outward to accommodate an adjacent protruding section of the house and basement window access.

Solar collector type also affects the heating capacity, but preliminary research indicated that the added expense of chrome-plated copper panels may not add enough efficiency to the SRRS design to be cost effective (Rhoads et al. 1995). Construction materials needed to build a complete SRRS including a solar panel are listed in the Do-It-Yourself guide (Klein 1993); those used in this study were all pre-

[9] While solar collectors at 90° receive only 86% of direct radiation striking collectors at the ideal tilt, they can receive up to 107% with indirect reflection.

[10] Plastic glazing may warp or melt at high temperatures. According to the Iowa Plastics Technology Center, most acrylics can withstand temperatures up to 65°C (150°F); polycarbonates are safe up to 120°C (250°F) (Ray Klemmensen, telephone interview, 1 September 1994).

manufactured flat-plate air collectors obtained from previous users[11] or vendor-donated. Additional installation supplies included temperature sensors, filters, ductwork, caulking, mounting materials, forced-draft fans, wiring, and dampers (Appendix D). Mechanical thermostats used in the previous SRRS design were replaced with National Semiconductor Precision Centigrade Temperature Sensors (LM35), connected to custom-designed electronic control units to regulate both heating and cooling temperature-based fan operation. Wiring diagrams are included in Appendix E.

Plastic-covered insulated flex ductwork was attached to solar panel outlets, passed through basement windows or holes cut into perimeter joists, and suspended from the basement ceilings with plumbers tape. Fasco 110 volt, 0.59 amp fan motors rated at 75 CFM were attached to the end of the ducts to discharge air centrally into the basements and wired into the control units; sheet metal dampers were attached to the fans' rectangular outlet flanges.

Radon Alarm and Mitigation Control

Since 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 be required to determine

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[11] Purchased with solar tax credits during the 1980s, many panels appropriate for SRRS installations are not currently in use may be found at garage sales and warehouses.

optimal system operation for additional dwellings. In order to simplify subsequent installations, newly available radon monitors which have the capability to activate fans based on radon levels were incorporated into the SRRS strategy.

Monitor Technologies Ltd. has developed a low-cost Radon Alarm (MTL-102), which activates a red warning light when radon reaches a programmable threshold, and a Mitigation Controller (MTL-106) to trigger operation of ventilation equipment. Radon is measured with a microprocessor-driven semiconductor α-particle detector which relies on passive air diffusion of sample air to the detection chamber; highly resistive photovoltaic cells track radon α-particle emission as voltage pulses.[12]

For statistical validity, an equally-weighted running average of the past 22 hours of radon measurements is displayed and updated every 82 minutes (the oldest 82-minute interval is cleared as each new count average is added into the 16 storage registers). Tested by the EPA's Office of Radiation Programs Las Vegas Facility, MTL Radon Alarms were found to be accurate within ±6%. However, when exposed to radon concentrations of 3.7- 28.4 pCi/L at 13-28°C at 35-60% relative humidity, the device exhibited variable bias from the true radon concentration dependent on environmental

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[12] Pulses specific to α 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 the pulse rate is directly proportional to surrounding radon concentration (Helmick 1994).

conditions; when subjected to combined conditions of low temperature (≥20°C) and low relative humidity (≥49%) the instrument was found to over-respond by up to 54.1% at levels near 4 pCi/L (Braganza and Levy 1992).

To verify MTL Radon Alarm measurements, duplicate testing with more sophisticated monitors or passive detectors and annual recalibration are recommended for radon professionals.[13] Nevertheless, the EPA praised its ease of use and avoidance of moving parts which often fail in other such devices, and approved it (Listing 2015800) both as a primary testing device and a secondary device for use in mitigation in the Radon Measurement Proficiency Program under EPA protocol for continuous radon monitors.

The accuracy of calibration of the six MTL Radon Alarms used in this study was tested both before and after the research periods in July 1994 and March 1995 and correction factors were calculated. The units initially stored only 10 hours of data internally; Radon Tools software (MTL-105) was later used to reconfigure parameters such as the mitigation threshold, duration of internal data storage (30 samples), and recording frequency (every hour). To ensure uninterrupted data collection, power supply backups were devised with Yuasa trickle-charge 12V 1.2 amp-hour gel-cell batteries. Null modem cables linking MTL Alarms to PC

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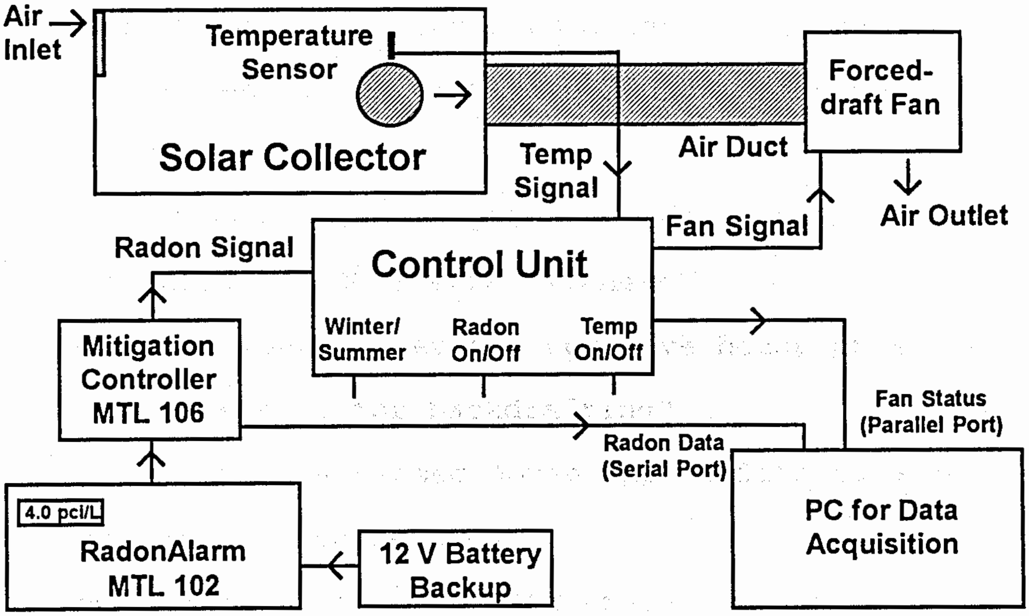
[13] Owner-users are advised to return units to the manufacturer for recalibration after 10 years.

serial ports were also devised; resistors prevented mitigation control transformers from overloading the battery backups (schematic in Appendix E). One cable was lengthened to activate Washington's SRRS based on first floor radon levels during the final test period.

Electronic Control Units

Control units were developed to combine radon and temperature SRRS trigger information as well as to enable PC monitoring of fan operation. Figure 8 depicts the complete SRRS and data acquisition setup; the control schematic is shown in Appendix E. Operational modes are set with exterior switches on the control unit; PCs record when the system is activated and deactivated based on a data line linked to the fan's power supply.

In the temperature-trigger mode, the SRRS fan is activated when the solar panel sensor reaches a specified temperature; for this study 20°C (68°F). When winter heating is selected, temperatures above the set point activate the fan, when adequate solar insolation pre-heats ventilation air or during warm outdoor conditions. With summer cooling setting, the fan is activated when temperatures drop below the set point during nights or cool days. To prevent excessive cycling, a timer-relay was added to ensure the fan is activated at least 3 minutes per run.



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

Figure 8. SRRS and data acquisition system block diagram

The radon-trigger mode activates the fan when the MTL Alarm reaches a programmable mitigation threshold; 3.0 pCi/L for most of the tests in this study. The combined temperature/radon-trigger mode activates the fan when either temperature or radon reach their set points.

Experimental Design

Research methodology was developed with the primary objective of measuring radon reduction and heat gain with varying hours of system operation in order to compare SRRS effectiveness and energy benefits at several houses. Key questions explored included:

- --Can radon be reduced with a net energy gain?
- --Can extended fan operation reduce radon below the EPA guideline?
- --How does house airtightness affect radon infiltration/SRRS effectiveness?
- --Does the SRRS alleviate negative house pressures and the potential for backdrafting?
- --Is a separate closed house appropriate as a "control" for mitigation testing?

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 the test mode sequence shown in Table 5. For the first four periods, the houses were divided into two groups and the four primary operational modes were alternated between groups to prevent entire test bias by weather or other time-related factors.

A fifth period was added in order to repeat tests in which instrumentation errors caused loss of data; this also allowed for site-specific testing. The winter temperature-trigger mode (WT) was repeated at Byron and Sager with timer-delay modified control units. To determine if first floor below-EPA guideline levels could be attained with less fan operation, Lovejoy and Vermont were tested in a winter temperature/radon-trigger mode (WR) with the (basement) radon threshold altered to 6.0 pCi/L; Washington was tested in the standard WR mode with its MTL Alarm moved to the first floor as a tighter control on living-space radon.

Table 5. SRRS Operational Test Modes

	Test Period	Operational Mode*					
		Control	**Byron**	**Lovejoy**	**Sager**	**Vermont**	**Washington**
1	12/05/94 - 12/15/94	CH	RT	RT	CH	RT	CH
2	12/20/94 - 12/30/94	CH	CH	CH	RT	CH	RT
3	01/03/95 - 01/13/95	CH	WR	WR	WT	WR	WT
4	01/17/95 - 01/27/95	CH	WT	WT	WR	WT	WR
5	01/31/95 - 02/10/95	CH	WT timer	WR6	WT timer	WR6	WRup

* CH = Closed House: fan off, duct sealed
RT = Radon-Trigger: activated at 3.0 pCi/L threshold
WT = Winter Temperature-Trigger: activated above 20°C
WR = Winter Temperature/Radon-Trigger: activated when >20°C or 3.0 pCi/L
timer = 3 min delay to prevent excess cycling
WR6 = Winter/Radon-Trigger with 6.0 pCi/L threshold
WRup = Winter/Radon-Trigger activated from 1st floor

Measurements and Data Acquisition

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

(Appendix C). 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.

Each SRRS test house was equipped with an MTL Radon Alarm and Mitigation Controller, an electronic control unit, and a computer data acquisition system for continuous datalogging (Fig. 8). Data collected included: radon levels and fan operation stored by Zenith PCs at all six houses; pressure differentials between the basement and outdoors, radiation striking the horizontal solar collector surface, temperatures and humidity stored with Campbell Microloggers at Lovejoy and Sager; and outlet temperatures stored by Omega Loggers at Byron, Vermont, and Washington (Table 6).

Directed by custom software (Appendix F), radon and fan status data were recorded with the PCs at hourly intervals, and fan operation was additionally logged each time the systems turned on or off. The dataloggers were programmed to store data at 12-minute intervals; methods for determining conversion factors and additional information on Omega Differential Pressure Transducers (PX-163-2.5 BD5V), Li-Cor Pyranometer light sensors (LI-200SA), fine-wire constantan/copper thermocouples, Vaisala Humitters, and other equipment used is included in Appendix D.

Additional data collected consisted of upstairs radon levels, measured with Honeywell Professional Radon Monitors

Table 6. Datalogging Plan

Goal: Determine radon reduction and energy benefits of SRRS
Location: 5 test houses and 1 control
Date: December 1994 to February 1995
Duration: 5 test periods, 10 days each

Test Modes:
CH Closed House
WT Winter Temperature-Trigger
RT Radon-Trigger
WR Winter Temp/Radon-Trigger

Zenith PCs: Control, Byron, Lovejoy, Sager, Vermont and Washington

Parameter	Sensor	Output/Range	Connection	Meas. Frequency	Data Storage
Basement Radon	Radon Alarm	Digital 0-199 pCi/L	Null Modem Serial Port	Download once/hour	Radon level, time and date in *.RAD file (Reading = 22 hour average)
Fan Operation	Control Unit Data Line	Analog 2.5 V	Signal 8, Ground 25 Parallel Port Pins	Monitor every 20 sec	Hourly status in *.RAD file Time and date of change in *.FAN file

Campbell 21X Microloggers: Lovejoy and Sager

Parameter	Sensor	Output/Range	Connection	Meas. Frequency	Processing	Conversion Factors
House Pressure Differential	Omega Pressure Transducer	Analog 0-5 V	Signal/Ground SE Ch 1 5V Excitation Ch 1	Sample once/minute	Average every 12 min	A: mV x 0.00393 - 8.395 = cm H2O B: mV x 0.00413 - 9.169 = cm H2O
Solar Radiation	Li-Cor Pyranometer	Analog 0-15 mV	Differential Ch 2 2220 adaptor	Sample once/minute	Average every 12 min	-12M: mV x 84.289 = W/m^2 -10M: mV x 71.429 = W/m^2
Temperature:						
Basement	21X Thermistor	-25 to 50°C	Internal	Sample once/minute	Average every 12 min	
Inlet, Outlet, Furnace Duct	3 Fine-Wire Thermocouples	Analog 0-5 mV	Differential Ch 3, 4, 5 Copper H, Const L	Sample once/minute	Average every 12 min	mV x 1 = °C
Humidity:						
Fan Outlet Furnace Duct	2 Humitters	Analog 0-5 V	Signal/Ground SE 1, 2 12 Excitation/Ground	Sample once/minute	Average every 12 min	mV x 0.1 = % RH

Omega RD-Temp Loggers: Byron, Vermont, and Washington

Parameter	Sensor	Output/Range	Connection	Meas. Frequency	Data Storage
Fan Outlet Temp	RD Thermistor	Digital -39 to 123°C	Serial Port DB-9/25 adaptors	Sample once/12 min	Downloaded to *.RTF file

(05-418)[14] at Lovejoy and Sager and AirChek Radon Test Kit and Enzone Radon Gas Detector mail-in activated charcoal samplers[15] at the remaining houses. Honeywell monitors can store up to 96 integrated average radon measurements internally during 4, 8, 12 or 24-hour intervals. The averaging interval of 8 hours was selected for this study; printouts were collected at the end of each test period and subsequently typed into a spreadsheet for data analysis. Charcoal radon mailers were opened in both the basement and first floors of all homes during the first period to establish radon gradients between floors as well as to verify MTL Alarm and Honeywell Monitor readings; subsequently they were used to measure upstairs radon levels at the homes without Honeywell monitors.

To supplement digital data acquisition, Dickson Temperature/Humidity Trace Recorders (THP7FM2) were used to document first floor environmental conditions at Lovejoy and Sager, and hours of furnace operation was noted for each period at Lovejoy. Indoor, outdoor, basement, and first

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[14] EPA-approved α-particle emission silicon detectors equipped with internal battery backup and tamper-sensing electronics to log movement and power interruptions. Honeywell reports its accuracy to be $\pm$1 pCi/L or $\pm$25% in conditions of 5-32°C and 25-85% relative humidity, with nominal sensitivity of 2.5 α decays per hour per pCi/L. Annual calibration tests are recommended, and monitors with correction factors below 0.5 or above 1.5 should be recalibrated by the manufacturer.

[15] EPA-certified activated charcoal exposed to indoor air over four-day periods; packages are sealed and mailed to manufacturers' laboratories for measurement. Air-borne radon concentrations are calculated based on the amount of radon decay products adsorbed on the charcoal, duration of exposure, and time passed between sealing and analysis; samplers received over eight days after the test obtain only estimated results.

floor conditions were also monitored with a Vaisala hand-held temperature/humidity sensor (HM 34), and gas and electricity use was recorded, at each house during site visits at the beginning and end of each test period. Local weather data including heating degree days (HDD)[16] were monitored with printouts obtained from the Waterloo National Weather Service office.

SRRS fan air speed at each site was measured with a Solomat hot-bead anemometer (429) at five locations (A-E) in the fan flange outlet, and average velocity was calculated with the formula

$$v = [3(A + B + C + D) + 4E] / 16,$$

as determined by grid analysis (Fig. 9). Air flow (m^3/s) was calculated as velocity times area and converted to CFM.

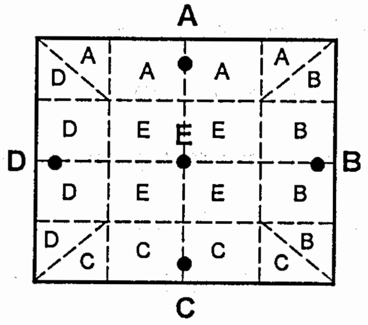

Figure 9. Location of SRRS fan outlet air flow measurements and grid analysis

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[16] A measure of daily mean temperatures below 18.3°C (65°F), commonly used as an index of heating fuel requirements. Each degree of mean temperature (in Fahrenheit) below 65 is counted as one HDD, so 10°C (50°F) = 15 HDD. If the daily mean temperature is $\geq$65°F, HDD = 0.

Data Processing/Analysis

The custom data acquisition software written in QBasic (Appendix F) recorded radon and fan status data on diskettes which were collected at the end of every test period. Setup and logout programs were also written to establish file names and store other information associated with each test period (Appendix F). Because the Zenith PCs' internal clocks could not retain memory in the event of power outage, the programs included a method of recalculating the current time based on battery-powered Radon Alarm clocks.

A custom program controlling 21X Micrologger measurements and internal processing (Appendix F) was stored on diskettes and loaded through PC-208 software; data from both the 21X loggers and RD-Temp loggers were downloaded through the Zenith PCs at each site onto floppy diskettes. All data files were compiled on a 486 PC hard drive and imported into Quattro Pro 6.0 for Windows. Graphs of real-time data were produced in Quattro Pro, and percentiles were statistically analyzed and graphed with Jandel SigmaStat/SigmaPlot. 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.

VI RESULTS

This chapter presents data obtained for this study, starting with calibration and radon mailer results and ventilation levels achieved with SRRS operation. Graphs of real-time radon, temperature, fan and pressure data are included for each test period at each house. Statistical distributions of radon data based on analysis of variance are then provided, and finally time-weighted averages of radon and the numerous parameters monitored are compiled.

Calibration and Radon Mailer Tests

Results of radon calibration tests conducted before and after the research periods are shown in Figures 10 and 11; Table 7 lists the location of each device during the research periods, means for both tests, and correction factors based on post-research test means compared to the charcoal mailer results.

Table 7. Radon Monitor Calibration Test Results

	Measuring Device	S/N	Location during Research	July 1994 Calibration Test Mean (pCi/L)	Difference from Group Mean	March 1995 Calibration Test Mean (pCi/L)	Difference from Group Mean	Correction Factor
	Air Chek Mailer	1748237				10.4		
A	MTL Radon Alarm	001016	Control	3.4	3.3%	11.4	-6.8%	0.91
B	MTL Radon Alarm	001085	Byron	3.5	6.1%	13.6	10.5%	0.76
C	MTL Radon Alarm	001083	Lovejoy	3.5	5.7%	15.7	22.6%	0.66
D	MTL Radon Alarm	001084	Sager	3.1	-4.5%	13.4	9.2%	0.78
E	MTL Radon Alarm	001030	Vermont	3.2	-4.1%	9.4	-29.5%	1.11
F	MTL Radon Alarm	001081	Washington	3.0	-8.3%	9.5	-28.1%	1.09
		Overall MTL monitor mean:		3.3		12.2		
		Std deviation of monitors:		0.18		2.30		
		Monitors calibrated within:		94.5%		81.1%		
G	Honeywell Radon Monitor	156648	Lovejoy 1st floor			11.0	0.9%	0.94
H	Honeywell Radon Monitor	156649	Sager 1st floor			10.8	-0.9%	0.96

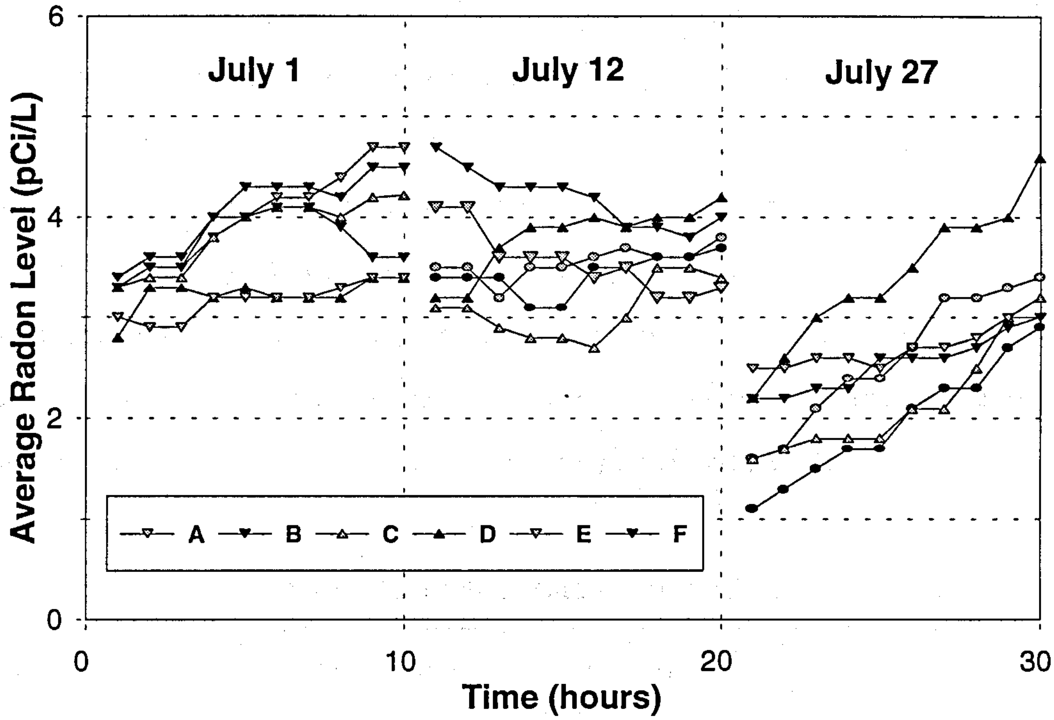


Figure 10. Calibration tests for six MTL Radon Alarms (A-F) at Byron basement, July 1994

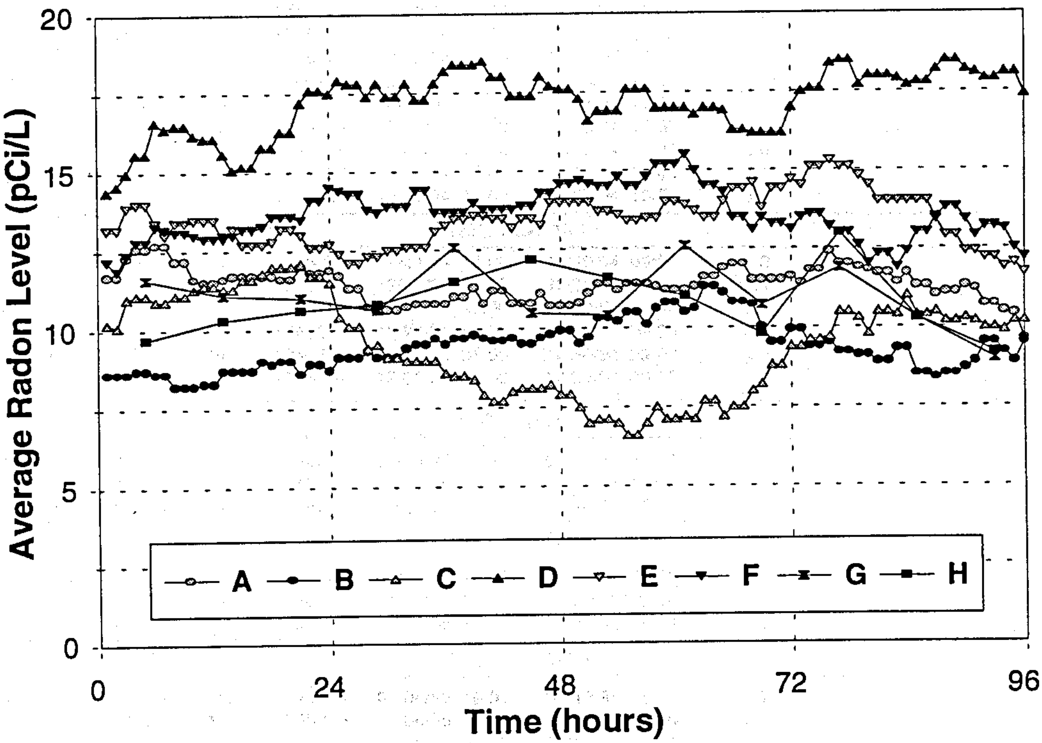


Figure 11. Post-research calibration tests for six MTL Radon Alarms (A-F) and two Honeywell Radon Monitors (G-H) at Sager basement, March 2-6, 1995

Results of charcoal radon testers used throughout the research periods are shown in Table 8. When mailers were used to duplicate monitor data (period 1), monitor means during the time the mailers were open are also shown with resulting correction factors. Due to mail delay, the manufacturer could not provide a result for the mailer placed in Lovejoy's basement, nor for three other mailers (out of 28) placed during the research periods.

Table 8. Activated Charcoal Mail-in Radon Tester Results

Site	Mode*	Floor	S/N	Start Time	Stop Time	Mailer Result (pCi/L)	MTL 4-day Mean (pCi/L)	Correction Factor
TEST PERIOD 1								
Control	CH	Bsmt	1748229	12/09/94 17:00	12/15/94 15:00	3.5	4.2	0.83
		1st	1748230	12/09/94 17:00	12/15/94 15:00	1.3		
Byron	RT	Bsmt	1748220	12/09/94 17:00	12/16/94 16:00	8.1	10.8	0.75
		1st	1748226	12/09/94 17:00	12/16/94 16:00	6.1		
		2nd	1748221	12/09/94 17:00	12/16/94 16:00	6.6		
Lovejoy	RT	Bsmt	1748222	12/10/94 14:00	12/17/94 10:00	n/a		
		1st	1748223	12/10/94 14:00	12/17/94 10:00	2.6	3.3	0.79
Sager	CH	Bsmt	1748232	12/09/94 17:00	12/15/94 13:00	11.0	15.2	0.72
		1st	1748231	12/09/94 17:00	12/15/94 13:00	12.4	12.7	0.98
Vermont	RT	Bsmt	1748224	12/09/94 17:00	12/16/94 17:00	5.7	10.2	0.56
		1st	1748225	12/09/94 17:00	12/16/94 17:00	5.0		
Washington	CH	Bsmt	1748228	12/10/94 12:00	12/17/94 12:00	4.1	2.8	1.46
		1st	1748227	12/10/94 12:00	12/17/94 12:00	3.9		
TEST PERIOD 2								
Control	CH	1st	1748235	12/24/94 13:00	12/30/94 09:00	1.2		
		2nd	1748236	12/24/94 13:00	12/30/94 09:00	1.4		
Byron	CH	1st	1748233	12/24/94 13:00	12/30/94 09:00	n/a		
Vermont	CH	1st	1748244	12/24/94 13:00	12/30/94 09:00	n/a		
Washington	RT	1st	1748243	12/26/94 08:00	12/30/94 09:00	4.0		
		2nd	1748234	12/26/94 08:00	12/30/94 09:00	3.3		
TEST PERIOD 3								
Byron	WR	1st	1748241	01/09/95 17:00	01/13/95 15:00	3.9		
Vermont	WR	1st	1748242	01/09/95 21:00	01/13/95 16:00	6.7		
Washington	WT	1st	1748238	01/09/95 11:00	01/14/95 17:00	3.5		
TEST PERIOD 4								
Byron	WT	1st	1748240	01/23/95 17:00	01/27/95 12:00	6.1		
Vermont	WT	1st	1748239	01/23/95 17:00	01/27/95 12:00	n/a		
Washington	WR	1st	533471	01/24/95 19:00	01/27/95 16:00	6.2		
TEST PERIOD 5								
Byron	WT timer	1st	1748294	02/06/95 19:00	02/10/95 15:00	7.7		
Vermont	WR6	1st	1748293	02/06/95 12:00	02/10/95 15:00	5.1		
Washington	WRup	Bsmt	533431	02/06/95 09:00	02/10/95 17:00	6.8		

**CH = closed house; RT = radon-trigger at 3 pCi/L threshold; WT = winter temperature-trigger with 20°C setpoint; WR = winter temp/radon-trigger; timer = 3 min delay to prevent excess cycling; WR6 = 6 pCi/L threshold; WRup = radon monitor on 1st floor*

Ventilation

Results of SRRS fan outlet air velocity measurements and air flow rate calculations (see Fig. 9) are shown in Table 9. Calculated house air time constants (hours per air change) based on blower door test natural infiltration estimates and added SRRS ventilation are shown in Table 10 and Figure 12.

Table 9. SRRS Air Flow Rates

Site	Dimensions (cm x cm)	Area (m^2 x 10^3)	Fan Status	Air Speed (m/s) A	B	C	D	E	Ave Air Speed (m/s)	Ave Air Flow (m^3/s)	Ave Air Flow (CFM)
Byron	5.6 x 6.8	3.8	ON	13.2	8.2	13.2	9.0	13.1	11.5	0.044	92
Lovejoy	4.5 x 7.0	3.2	ON	13.2	13.2	13.2	13.2	13.2	13.2	0.042	89
Sager	5.6 x 6.8	3.8	ON	13.0	13.0	13.0	13.0	13.0	13.0	0.049	105
Vermont	5.6 x 6.8	3.8	ON	10.1	10.1	10.1	9.1	10.4	10.0	0.038	80
Washington	5.6 x 6.8	3.8	ON	9.0	7.9	7.3	9.0	5.9	7.7	0.029	62
Sager	5.6 x 6.8	3.8	OFF	1.9	2.8	2.8	3.0	2.0	2.5	0.009	20
Washington	5.6 x 6.8	3.8	OFF	-	0.7	-	0.6	0.5	0.4	0.001	3

Table 10. Time Constants of Natural and SRRS Ventilation

Test House	Volume (ft^3)	Natural Infiltration (CFM)	(ACH)	Natural Time Constant (Hrs/AC)	SRRS Ventilation (CFM)	(ACH)	Combined Ventilation (ACH)	Combined Time Constant (Hrs/AC)	Time Constant Reduction
Control	18,150	385	1.27	00:47	75	0.25	1.52	00:39	16%
Byron	13,474	156	0.69	01:26	92	0.41	1.10	00:54	37%
Lovejoy	21,184	62	0.18	05:41	89	0.25	0.43	02:20	59%
Sager	13,232	100	0.45	02:12	105	0.47	0.93	01:04	51%
Vermont	11,655	91	0.47	02:08	80	0.41	0.88	01:08	47%
Washington	18,425	196	0.64	01:34	62	0.20	0.84	01:11	24%

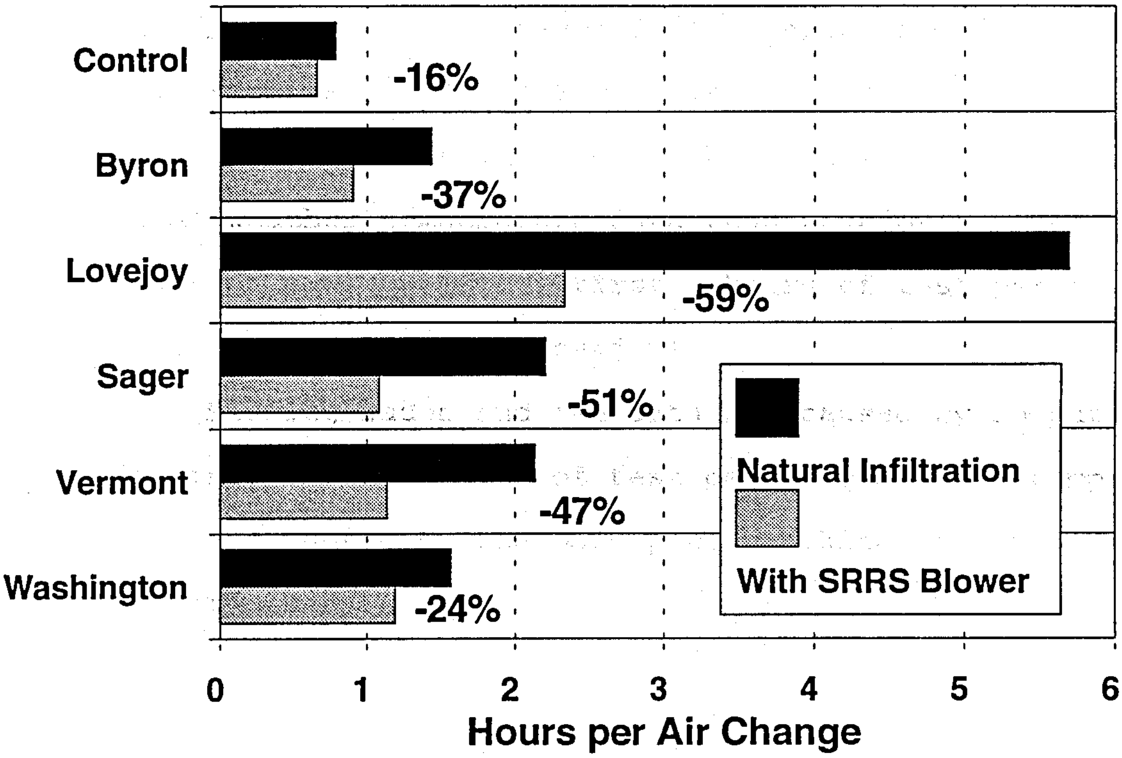


Figure 12. Effect of SRRS operation on house air time constants based on blower door and air flow measurements

Real-Time Radon, Temperature and Pressure Data

Real-time data collected at Control, Byron, Lovejoy, Sager, Vermont and Washington during the five test periods, December 5, 1994 through February 10, 1995 are shown in Figures 13-43. Grid lines for the x-axis fall on midnight of each day during the test periods shown. The MTL Radon Alarm data points represent a moving average of the previous 22 hours, while the Honeywell monitor data points signify eight-hour averages.

Charcoal mailer results are shown as first and second floor radon levels for houses without Honeywell monitors, and for Washington's basement for period 5. Fan inlet temperatures shown for Byron, Vermont, and Washington were taken from Sager's inlet data which were more similar to local weather temperature data than Lovejoy's, except where Sager data was missing (first 3 hours of test period 3, which were taken from Lovejoy).

Missing radon and fan data was caused by computer disks filling before the end of test periods; missing temperature data was caused by thermocouples breaking or sensors falling out of place.

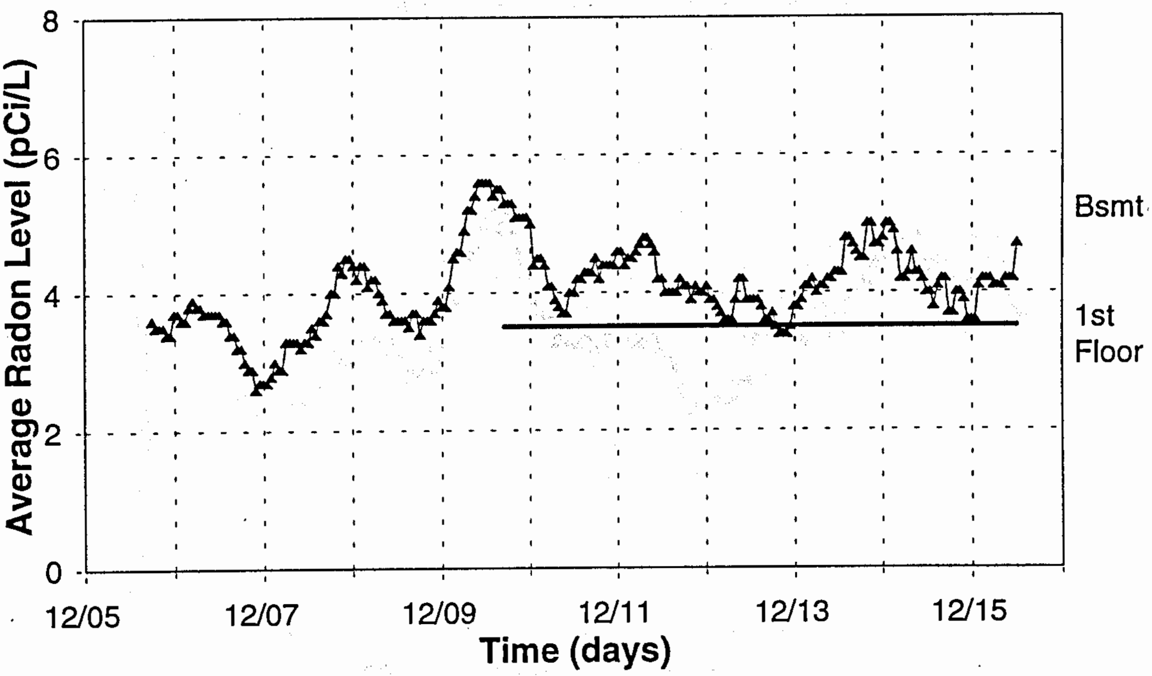


Figure 13. Control under closed house conditions, period 1: basement and 1st floor radon data

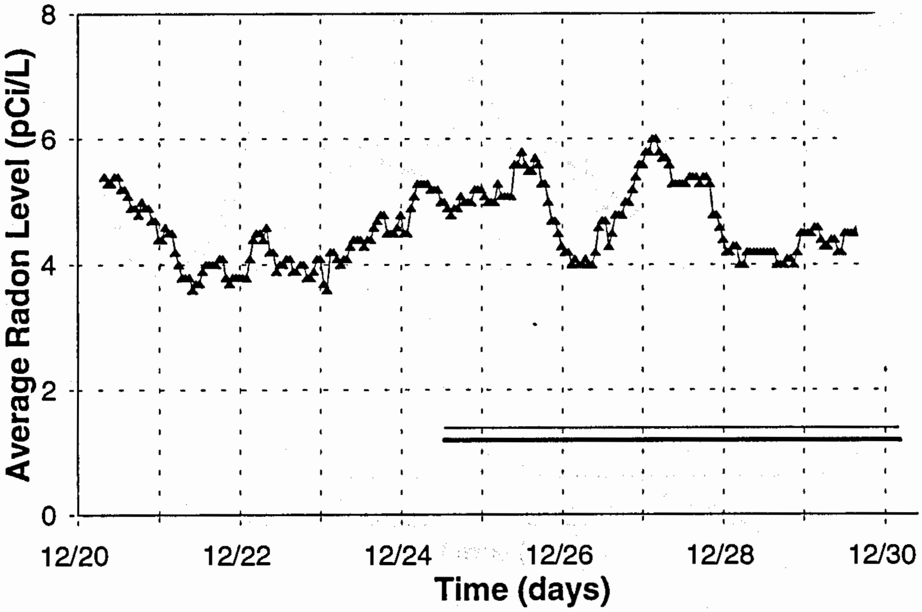


Figure 14. Control closed house, period 2: basement, 1st, and 2nd floor radon data

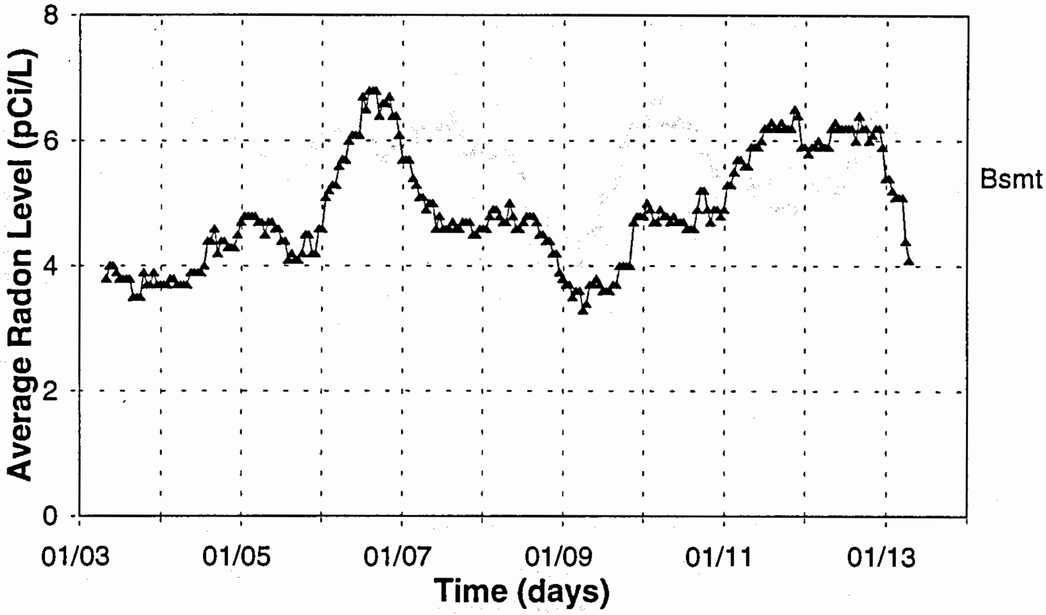


Figure 15. Control closed house, period 3 radon data

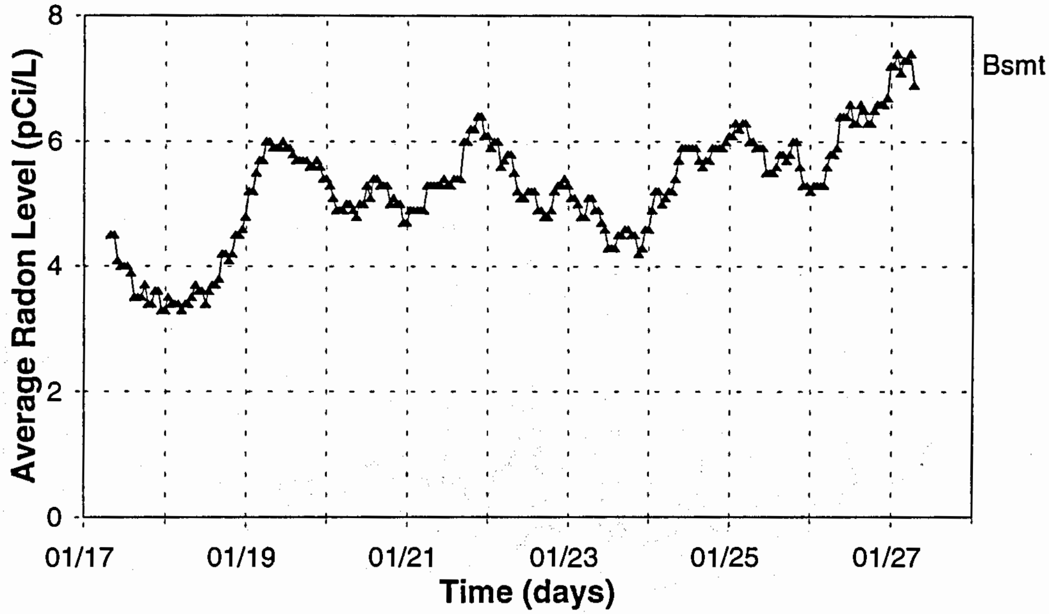


Figure 16. Control closed house, period 4 radon data

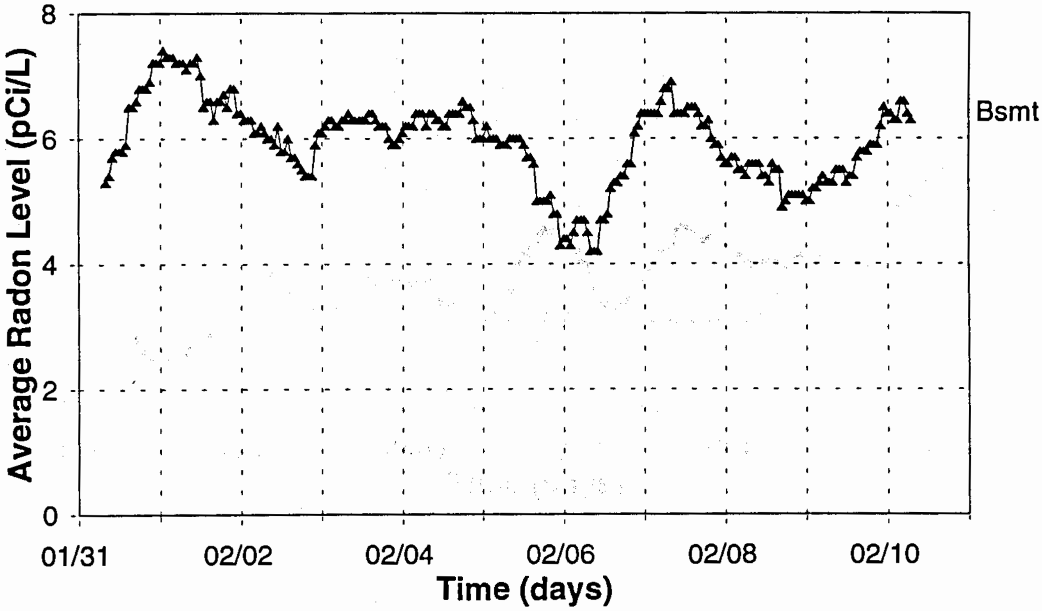


Figure 17. Control closed house, period 5 radon data

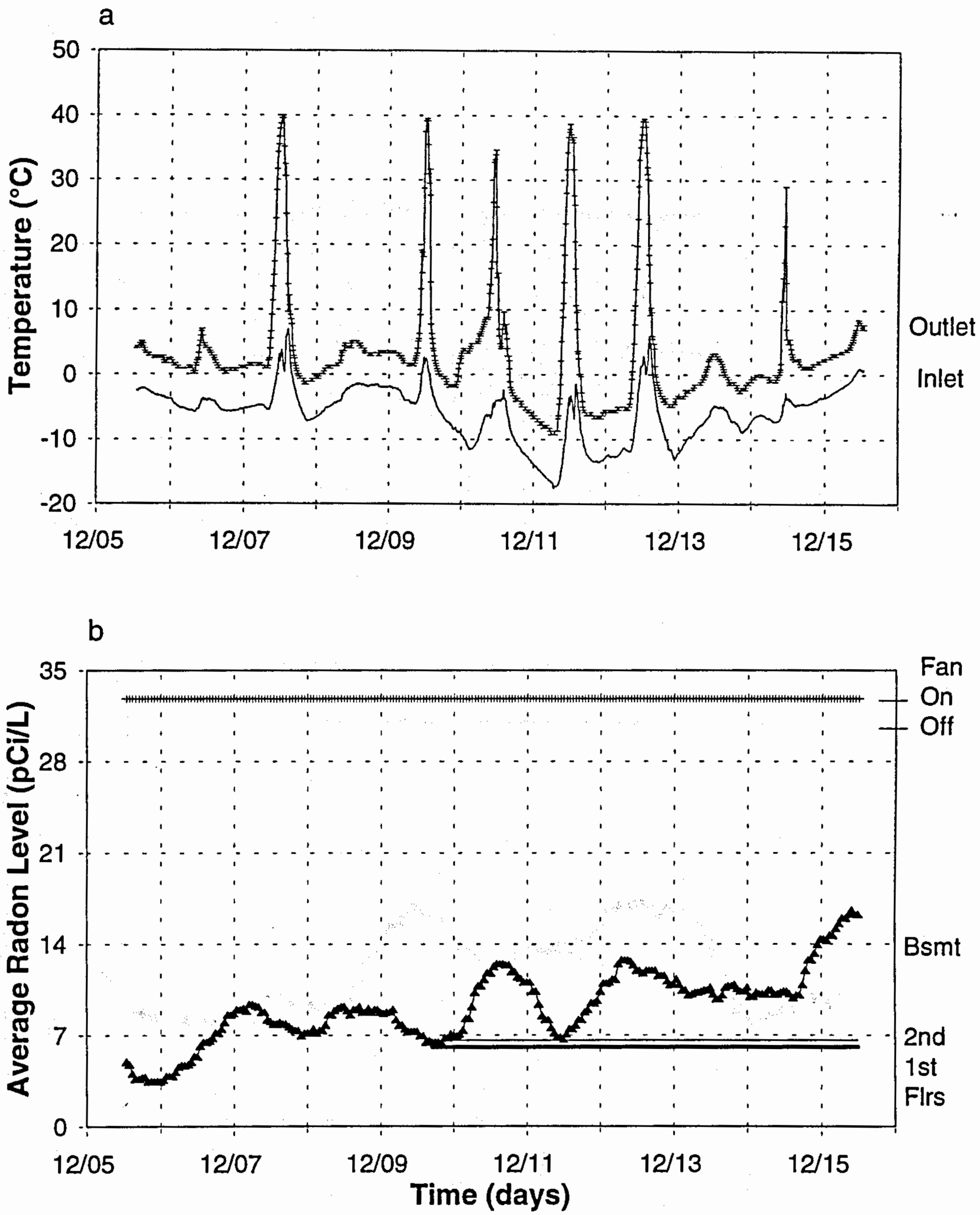


Figure 18. Byron with radon-trigger SRRS operation, period 1: (a) fan outlet and inlet temperatures; (b) fan status and radon data

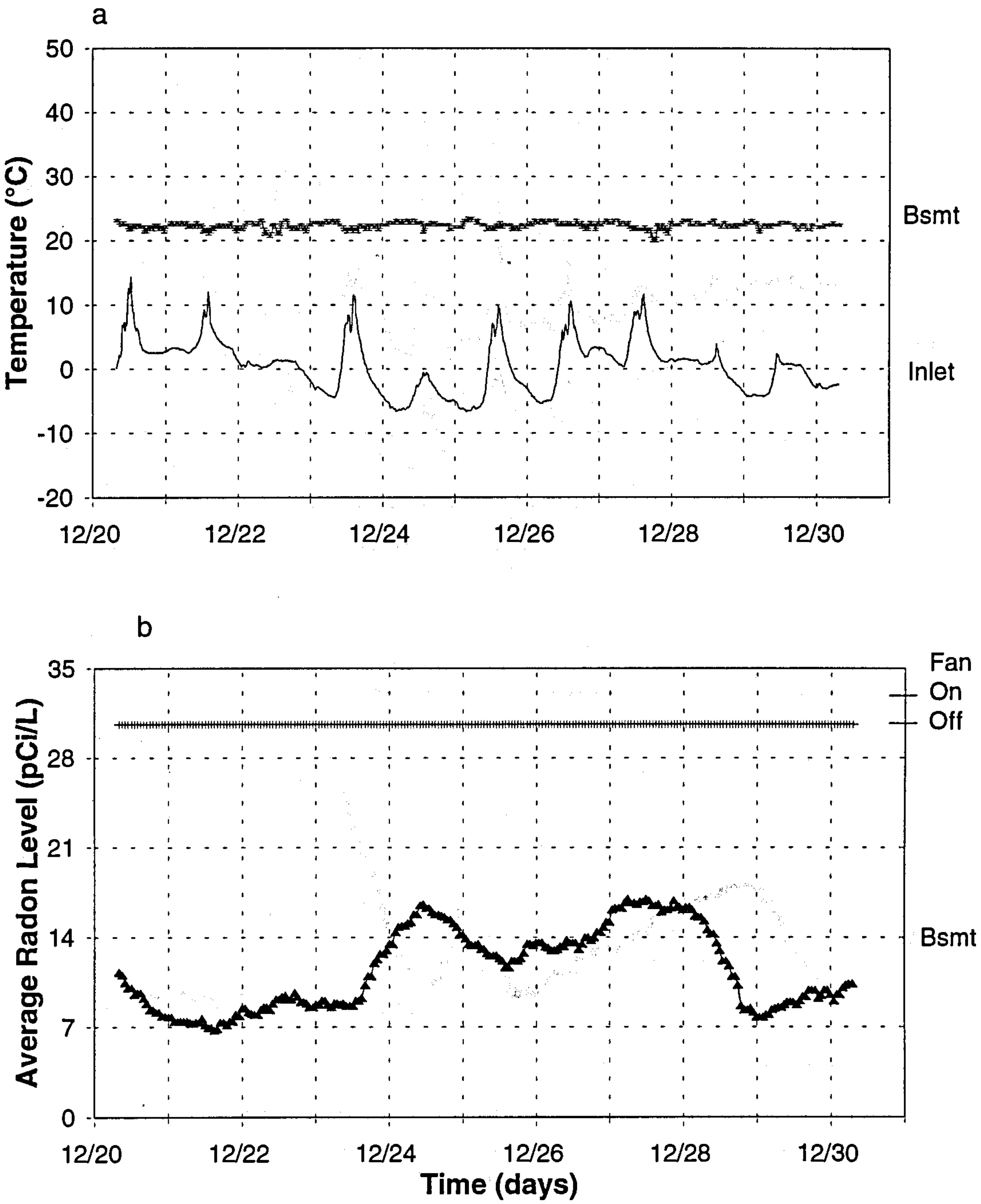


Figure 19. Byron closed house, period 2: (a) basement and outdoor temperatures; (b) fan and radon data

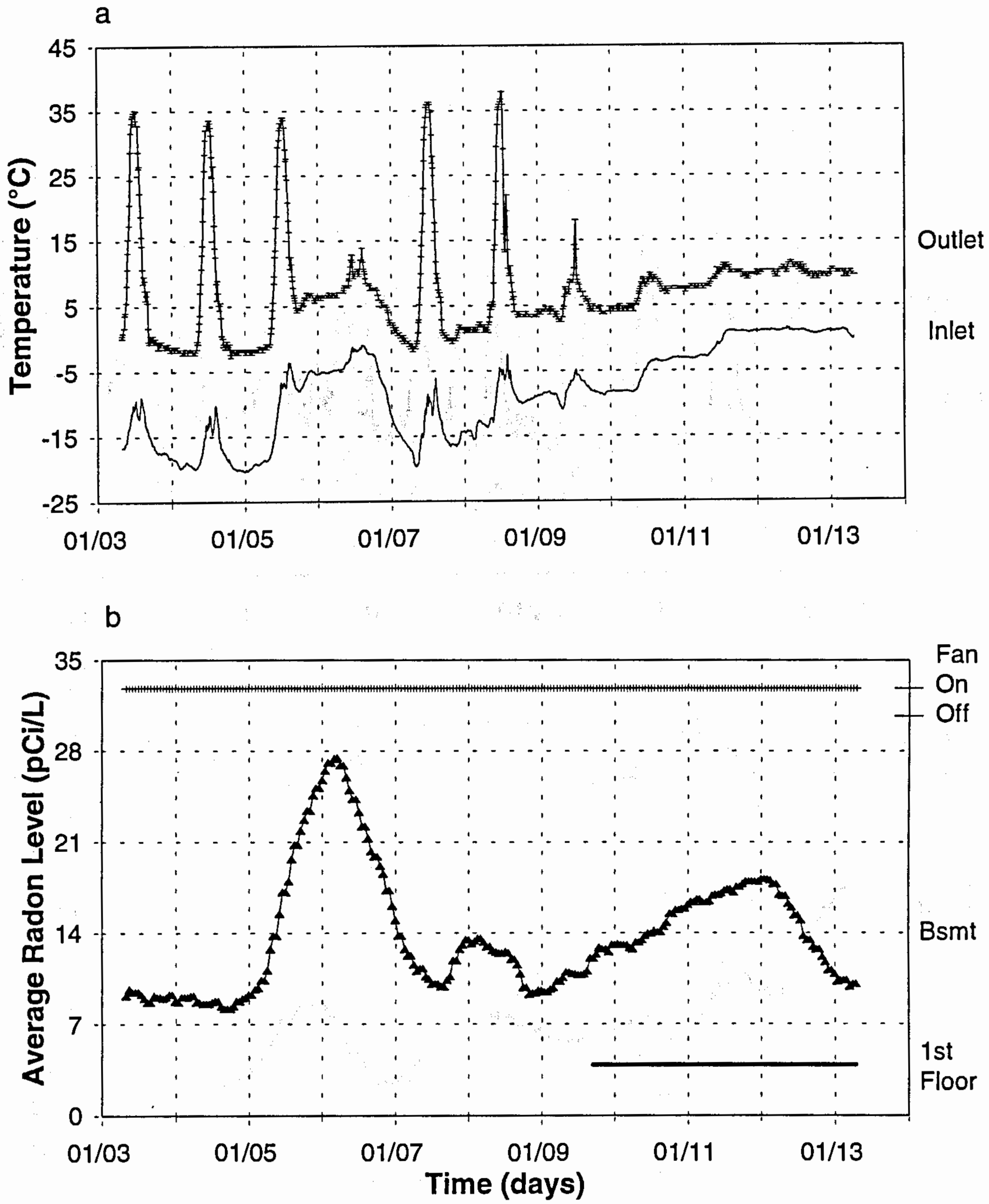


Figure 20. Byron temp/radon-trigger, period 3: (a) outlet and inlet temperatures; (b) fan and radon data

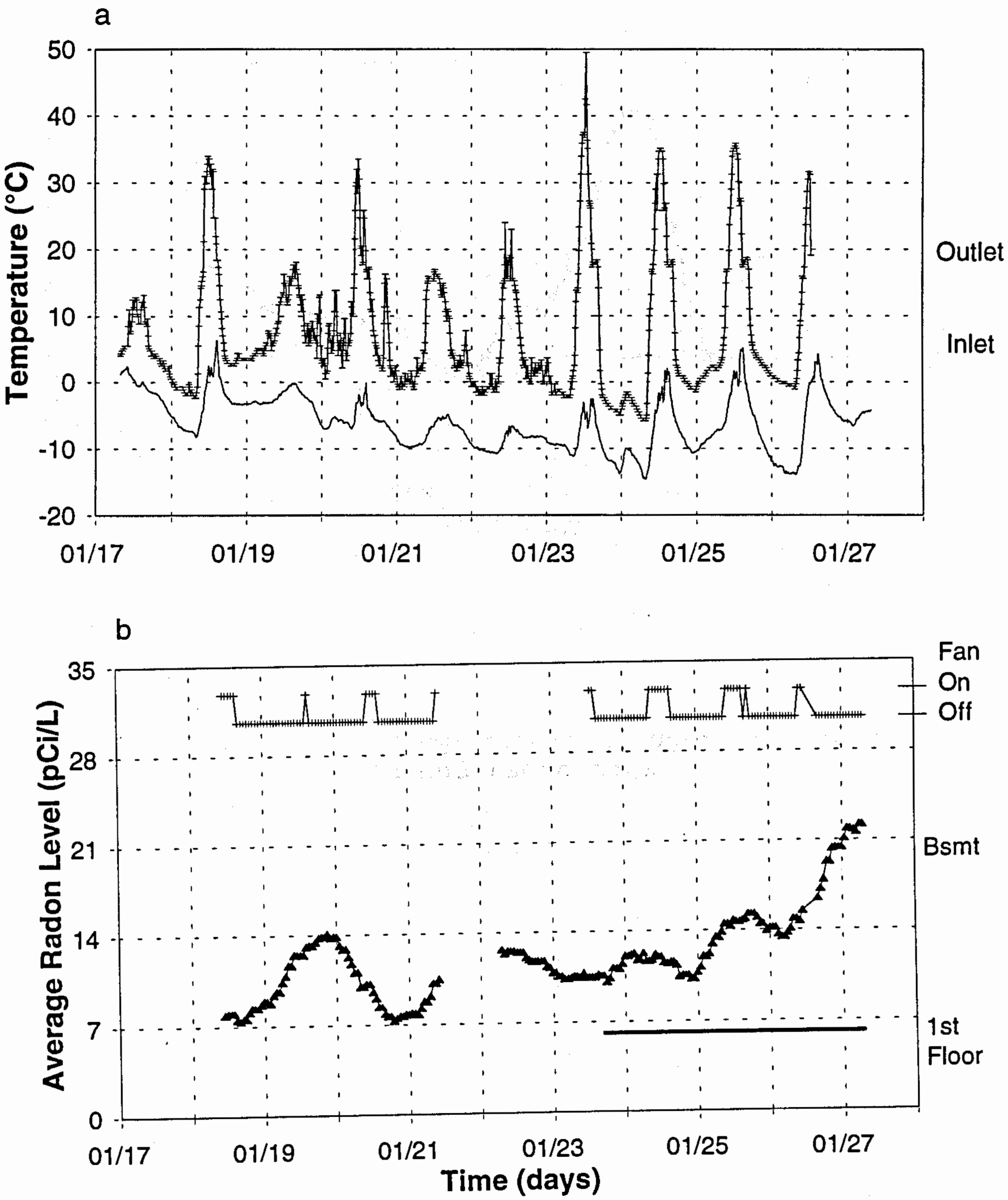


Figure 21. Byron temperature-trigger, period 4:
(a) temperatures; (b) fan and radon data

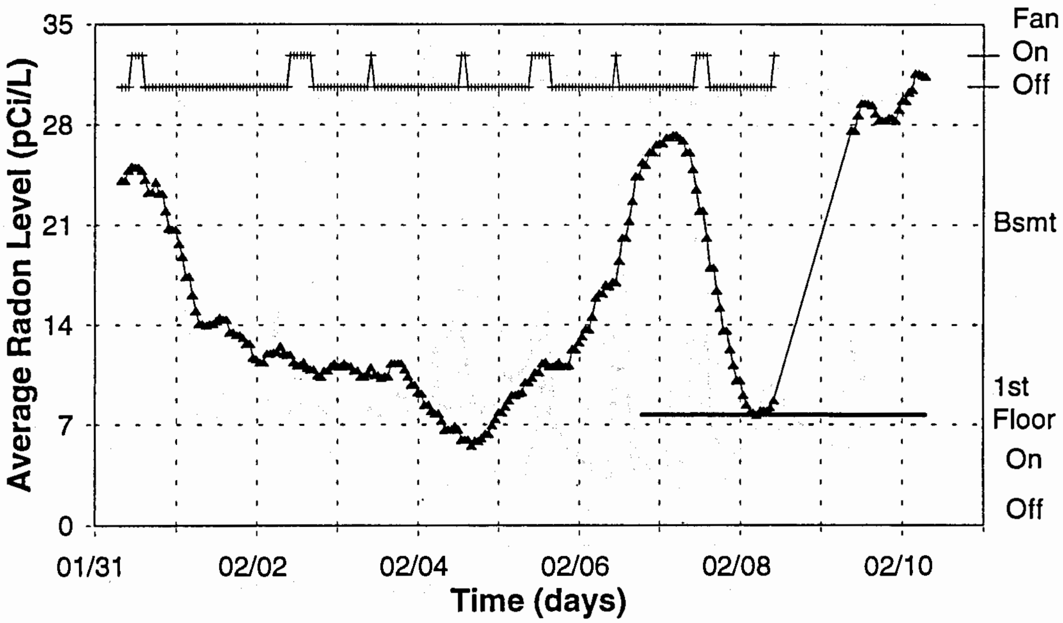


Figure 22. Byron temperature-trigger, period 5 fan and radon data

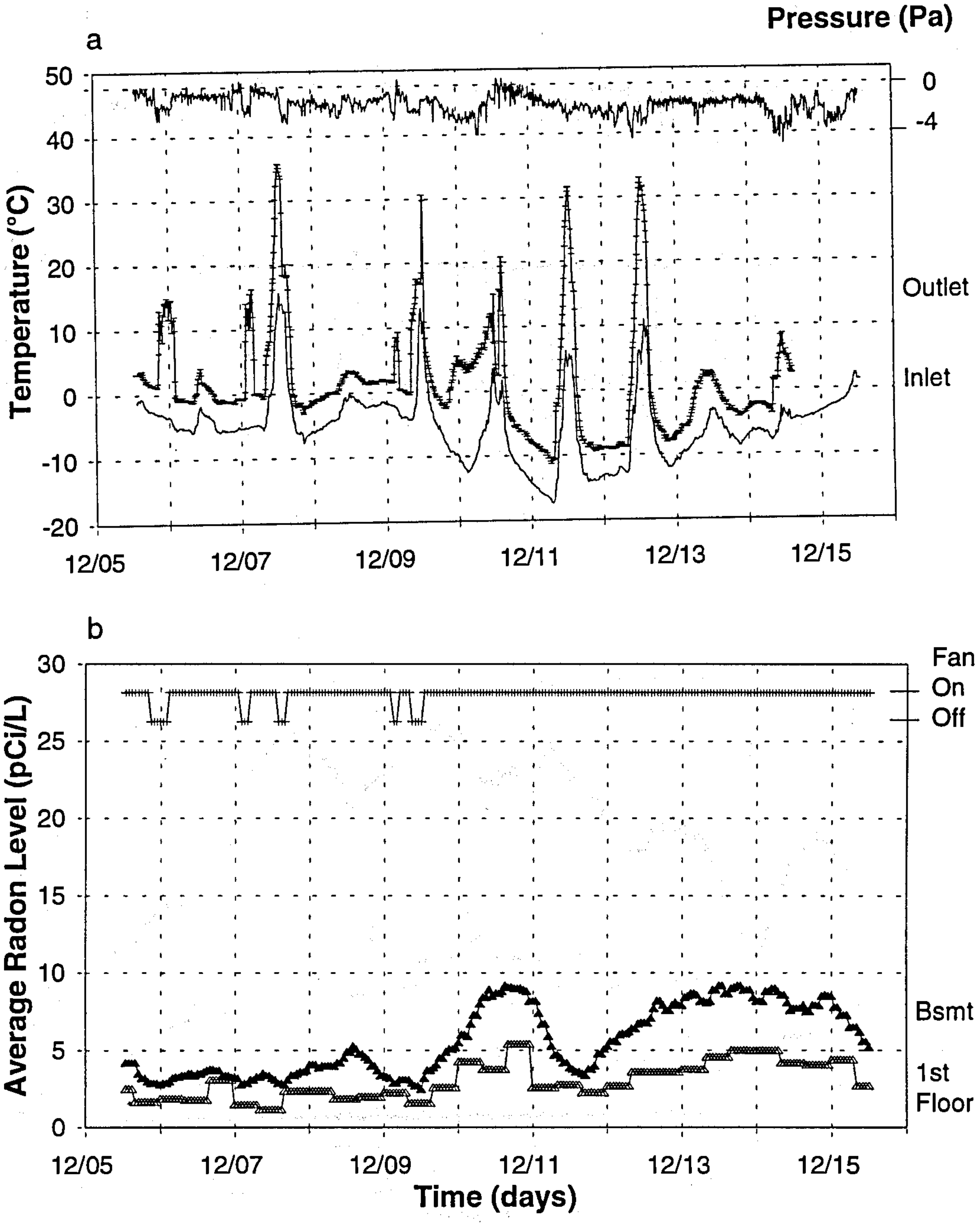


Figure 23. Lovejoy radon-trigger, period 1: (a) house pressure and temperatures; (b) fan and radon data

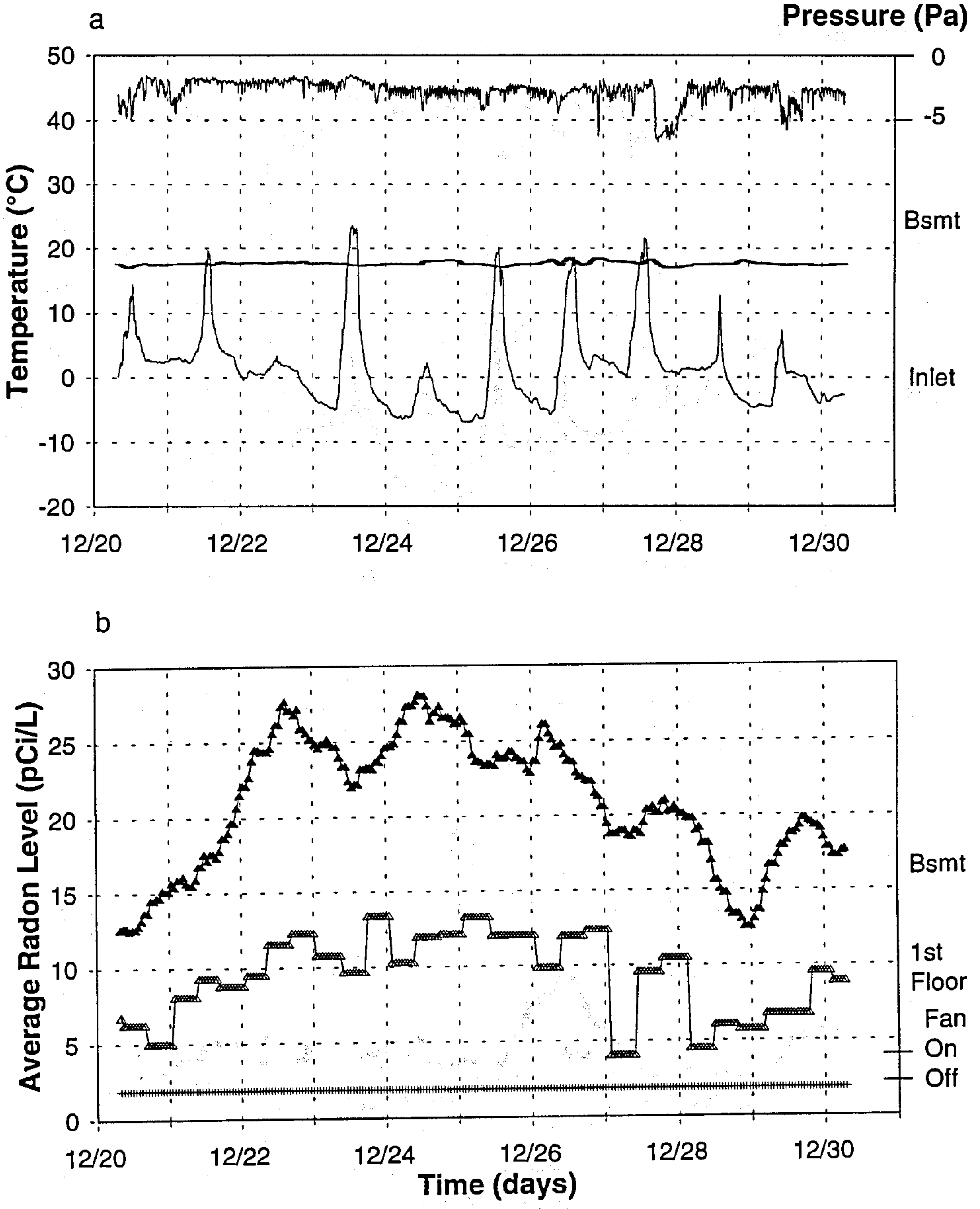


Figure 24. Lovejoy closed house, period 2: (a) pressure and temperatures; (b) fan and radon data

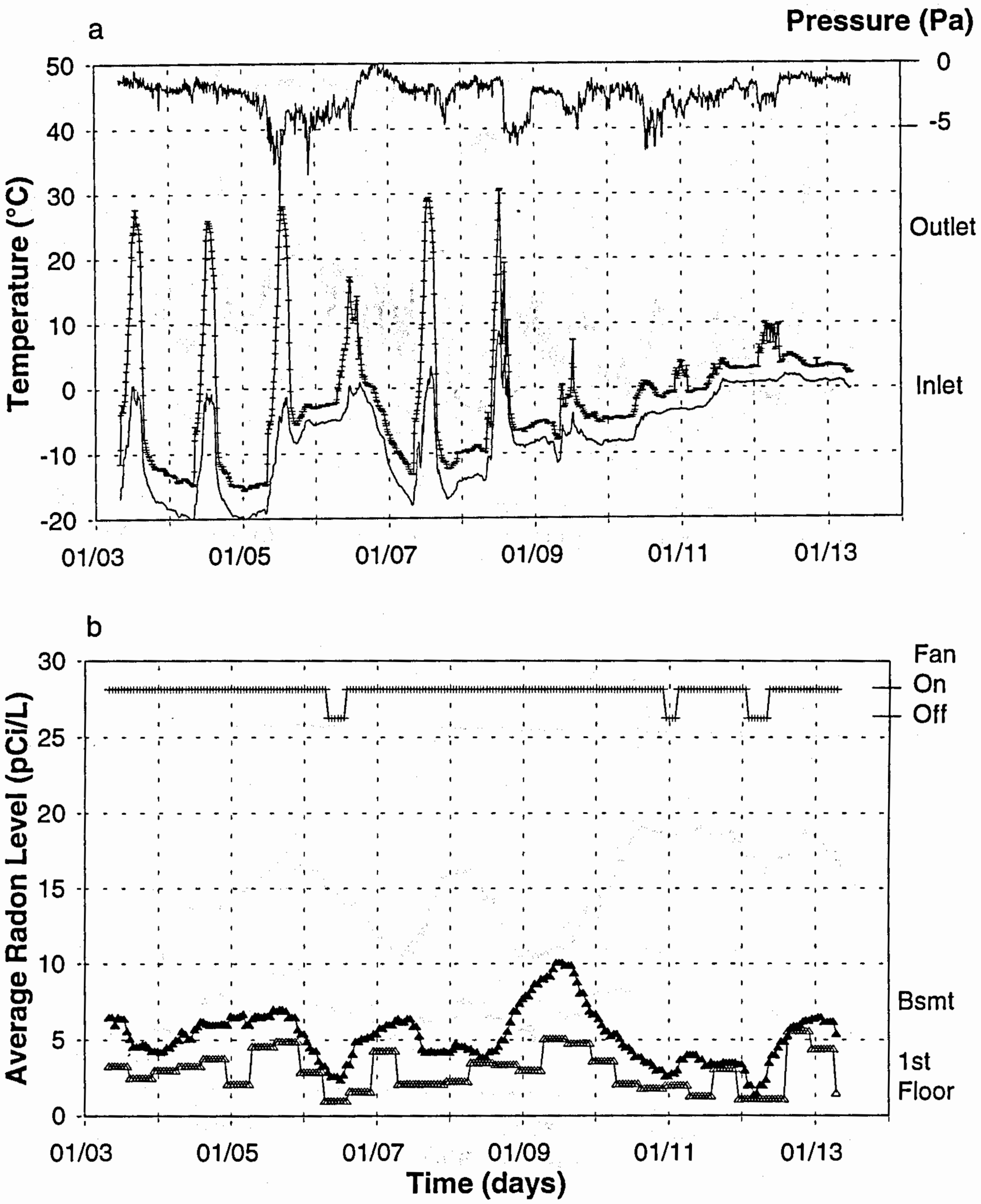


Figure 25. Lovejoy temperature/radon-trigger, period 3: (a) pressure and temperatures; (b) fan and radon data

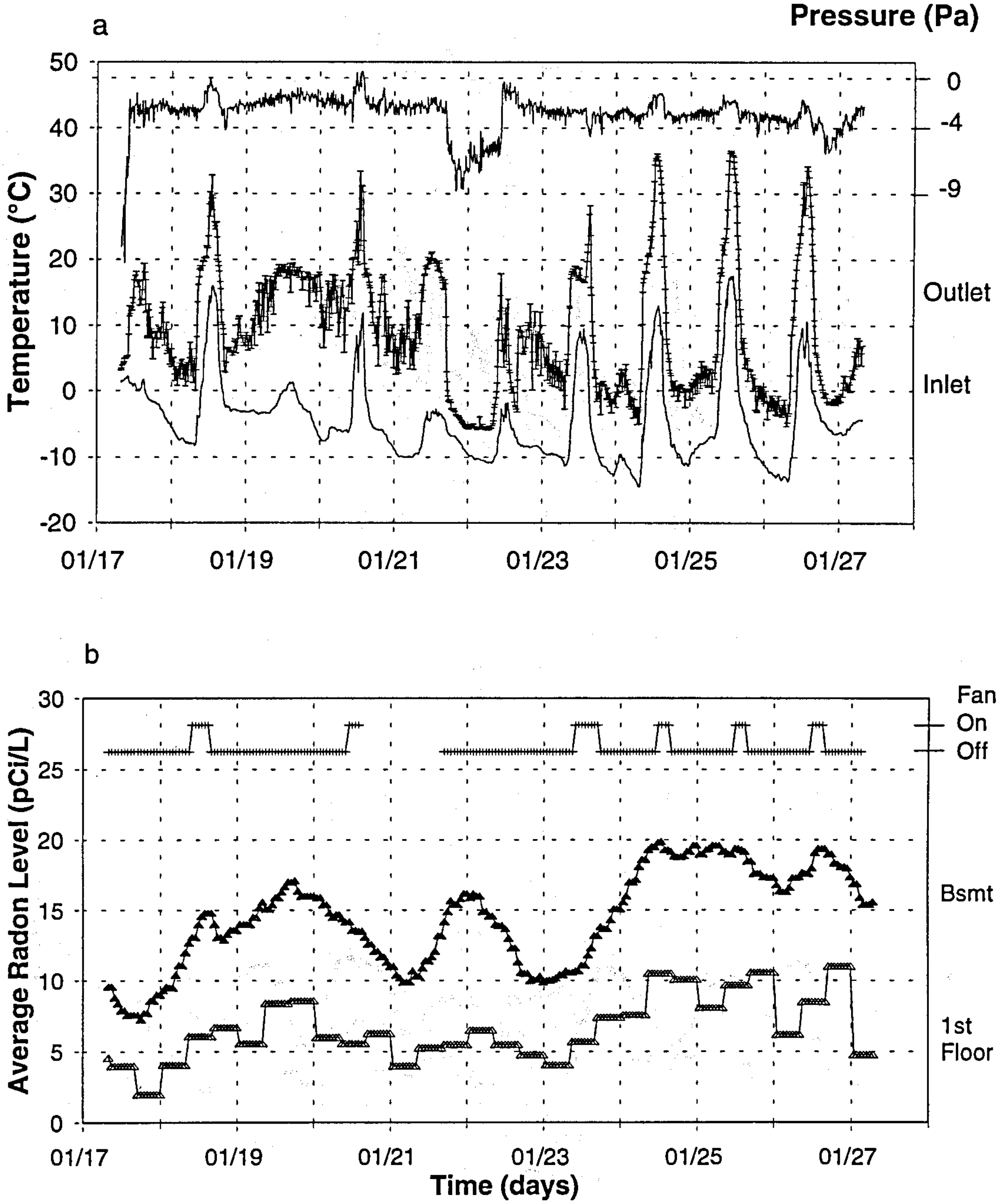


Figure 26. Lovejoy temperature-trigger, period 4: (a) pressure and temperatures; (b) fan and radon data

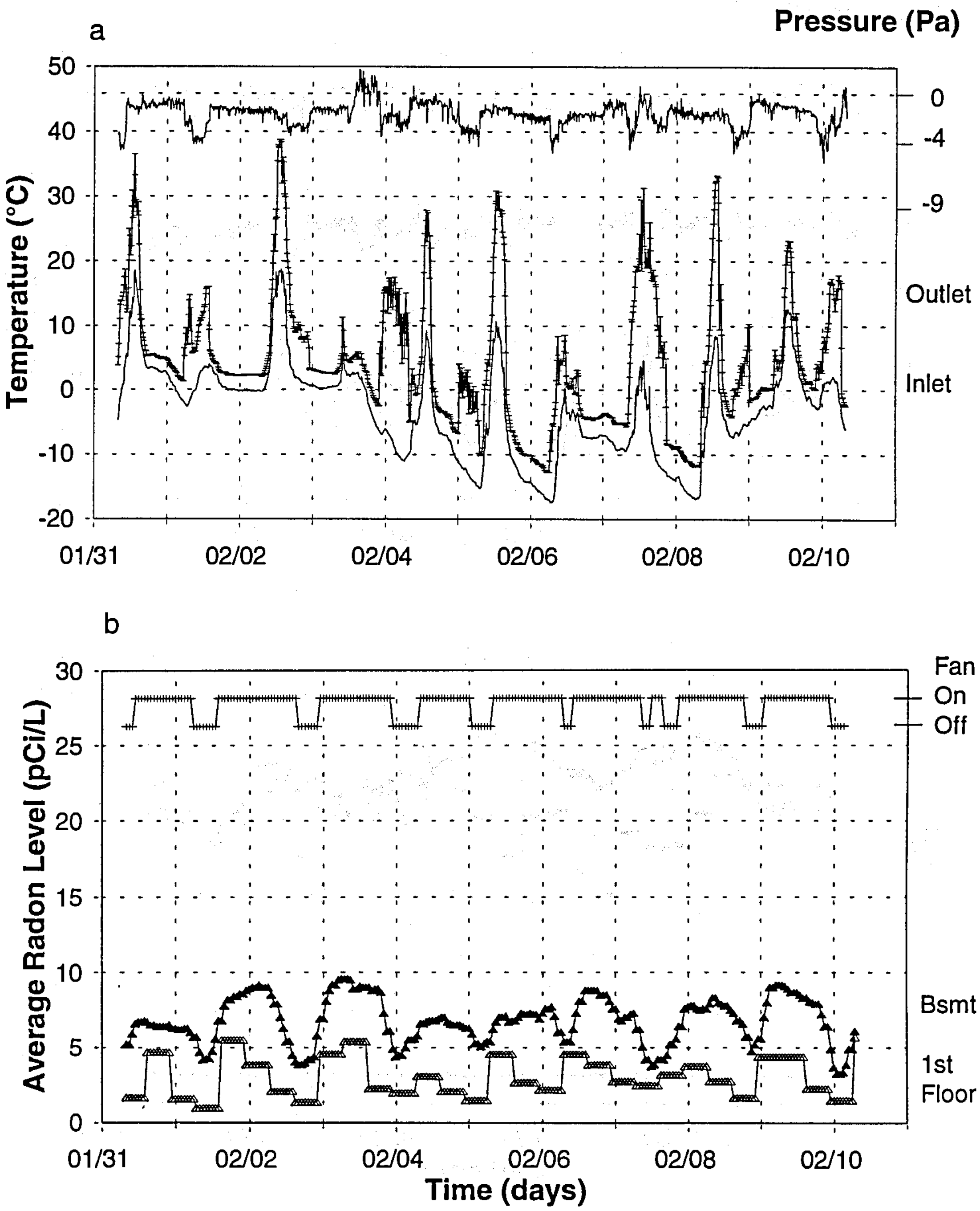


Figure 27. Lovejoy temperature/radon-trigger (6.0 pCi/L threshold), period 5: (a) pressure and temperatures; (b) fan and radon data

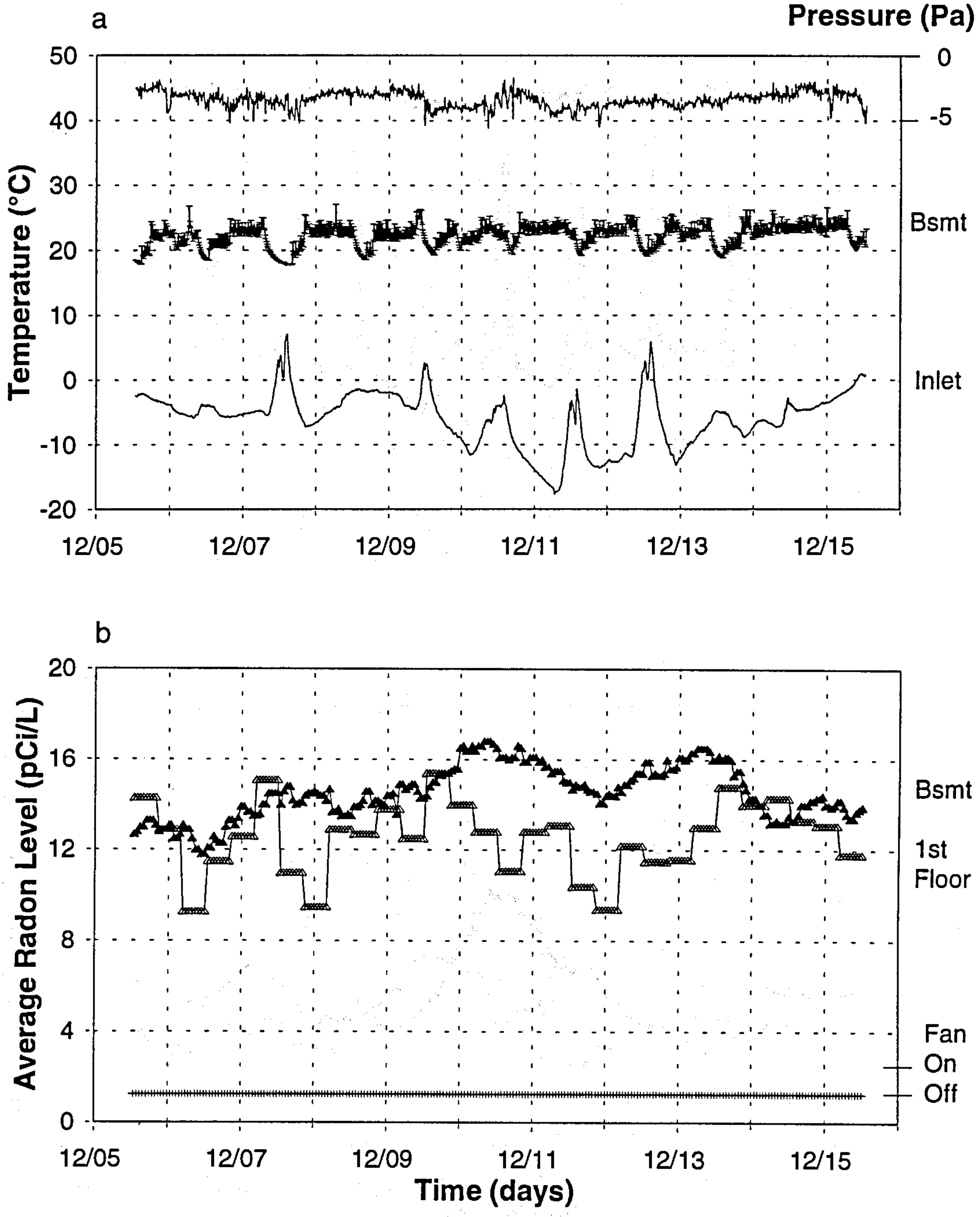


Figure 28. Sager closed house, period 1: (a) pressure and temperatures; (b) fan and radon data

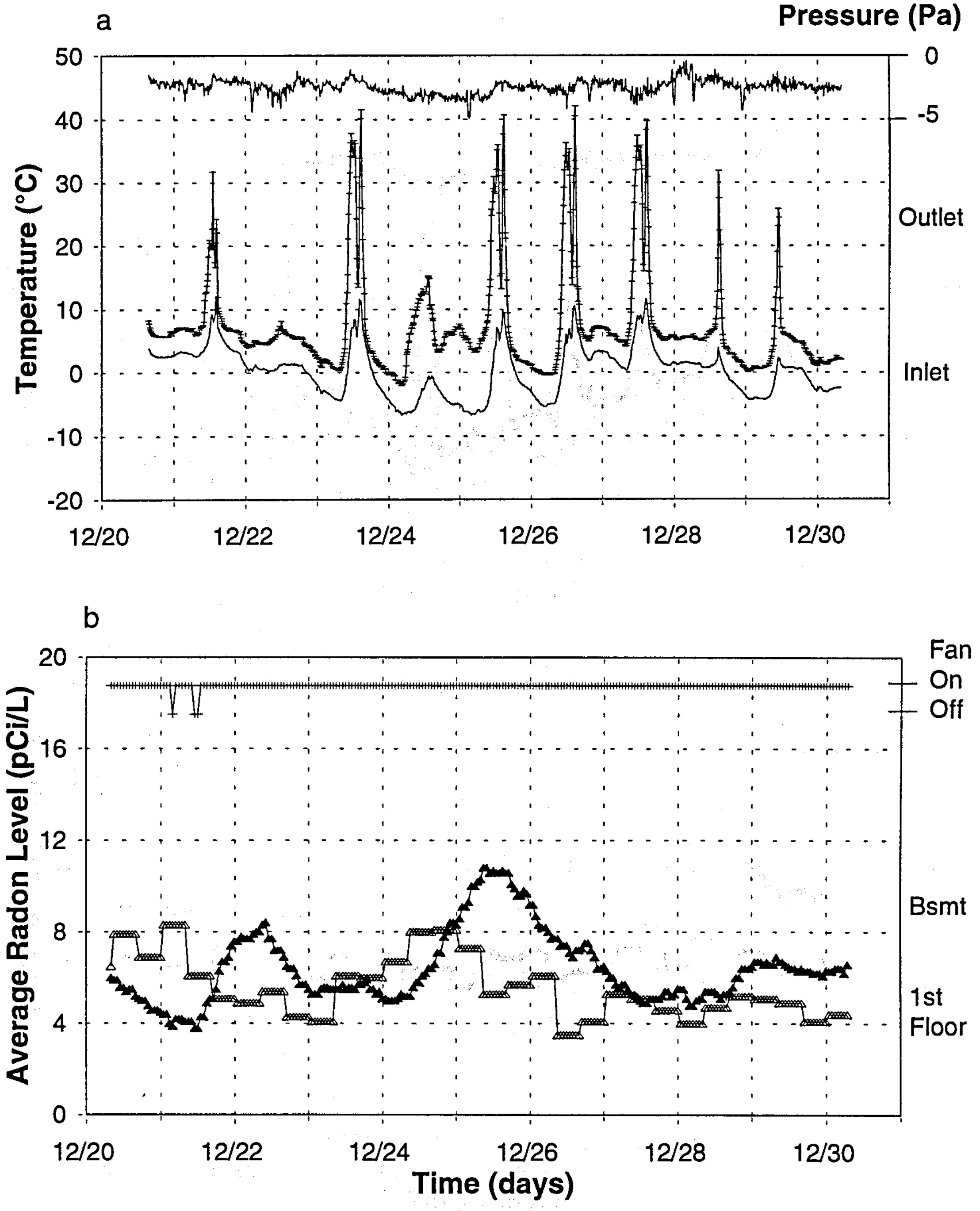


Figure 29. Sager radon-trigger, period 2: (a) pressure and temperatures; (b) fan and radon data

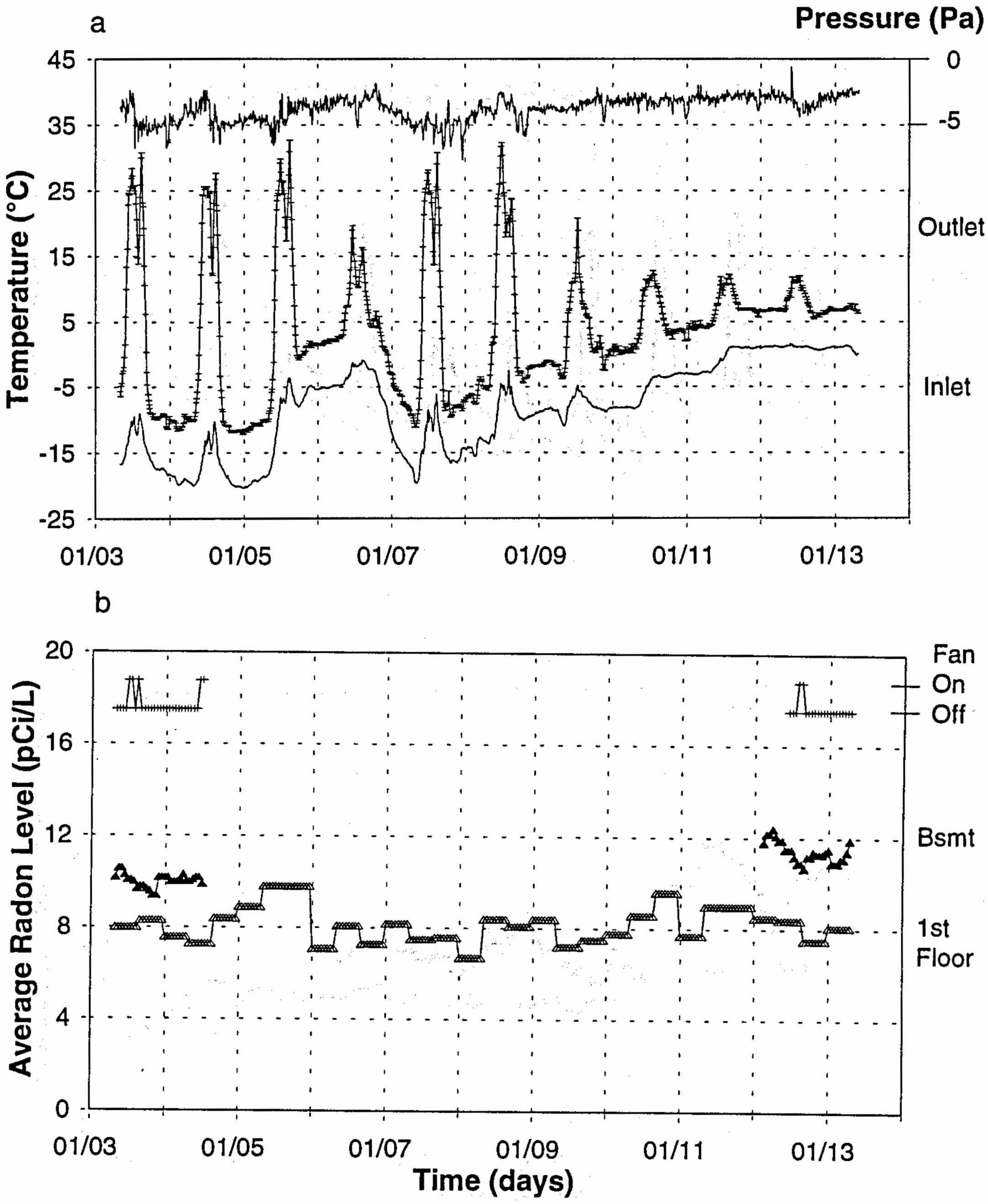


Figure 30. Sager temperature-trigger, period 3:
(a) pressure and temperatures; (b) fan and radon data

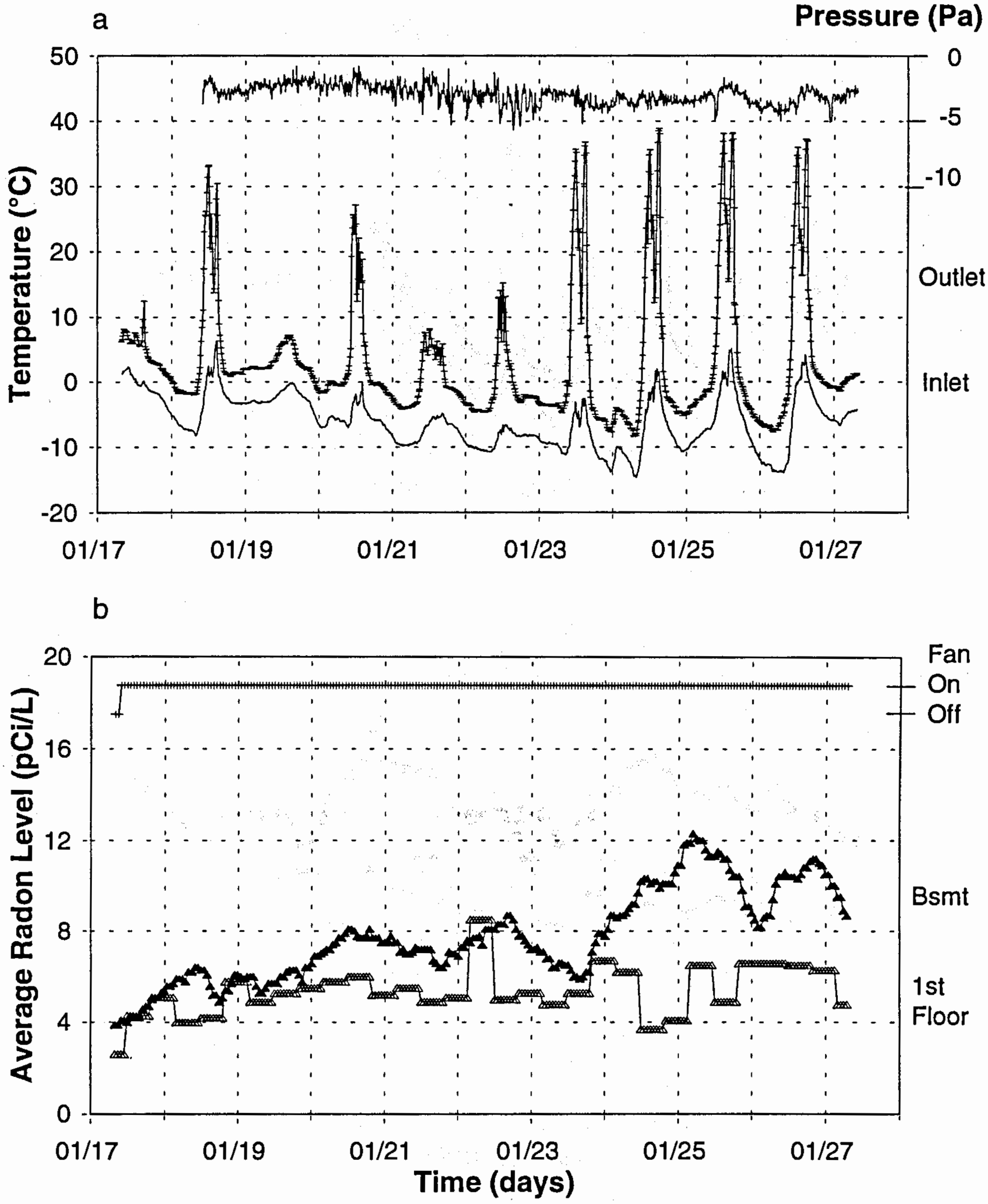
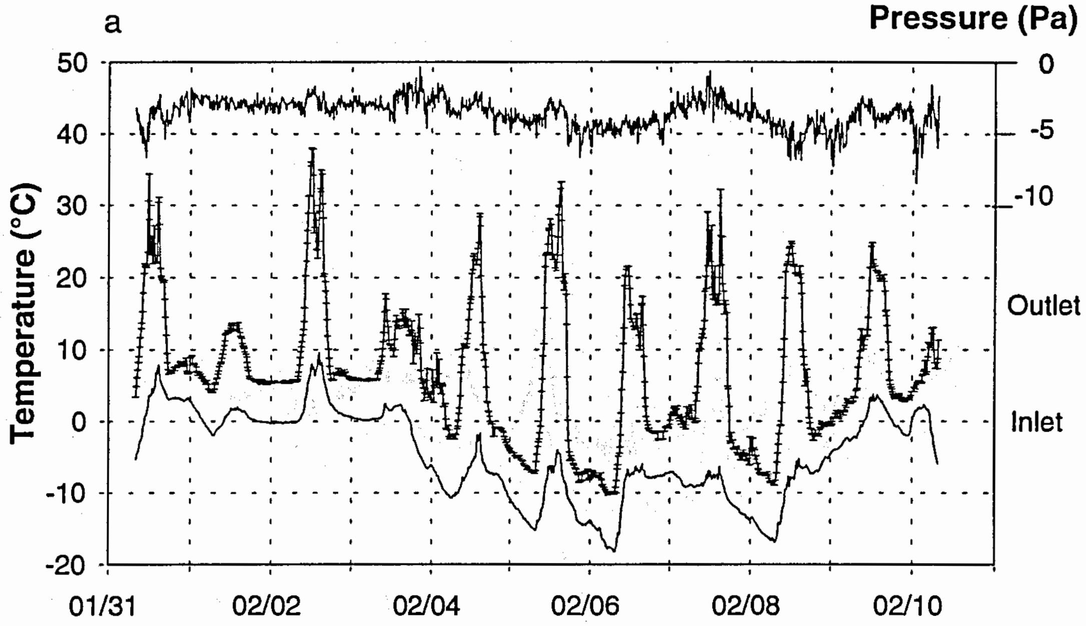


Figure 31. Sager temperature/radon-trigger, period 4: (a) pressure and temperatures; (b) fan and radon data



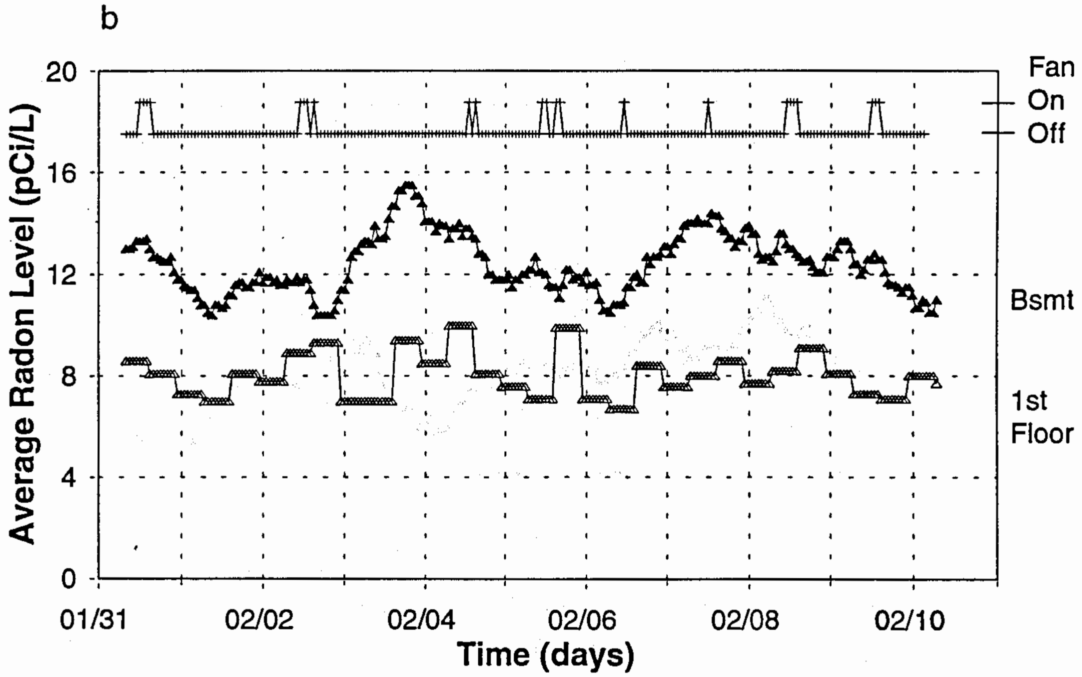


Figure 32. Sager temperature-trigger, period 5:
(a) pressure and temperatures; (b) fan and radon data

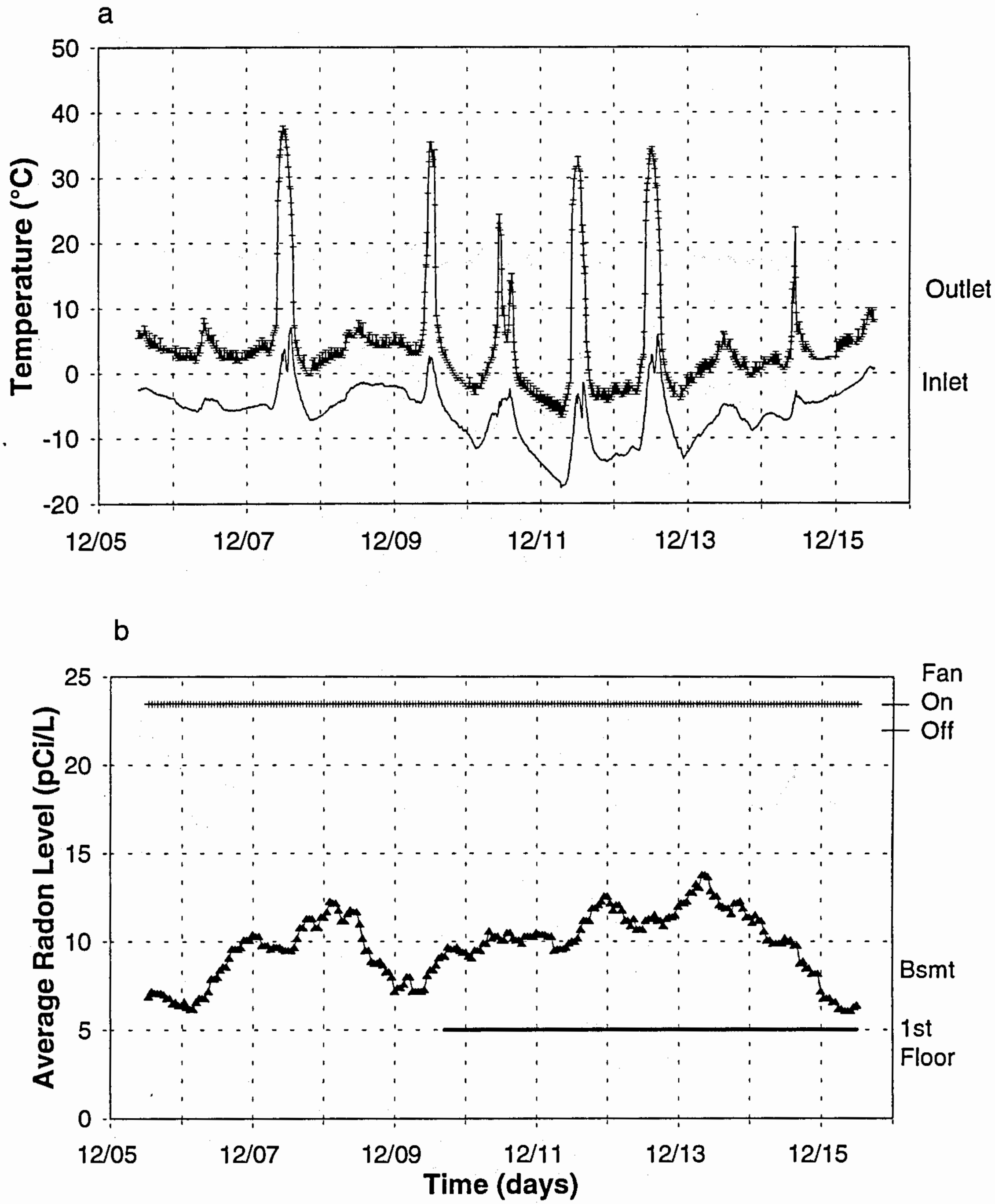


Figure 33. Vermont radon-trigger, period 1:
(a) temperatures; (b) fan and radon data

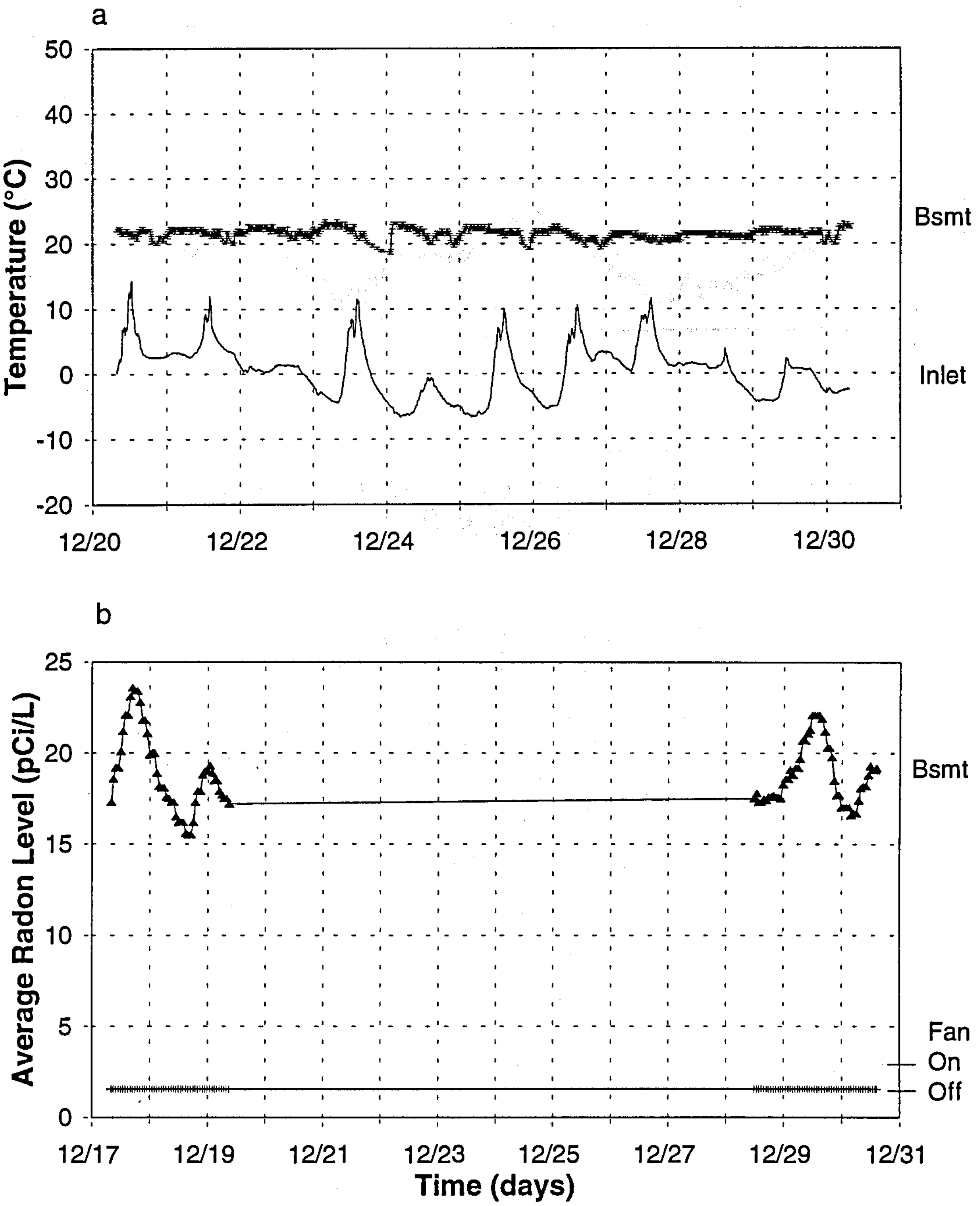


Figure 34. Vermont closed house, period 2: (a) temperatures; (b) fan and basement radon data

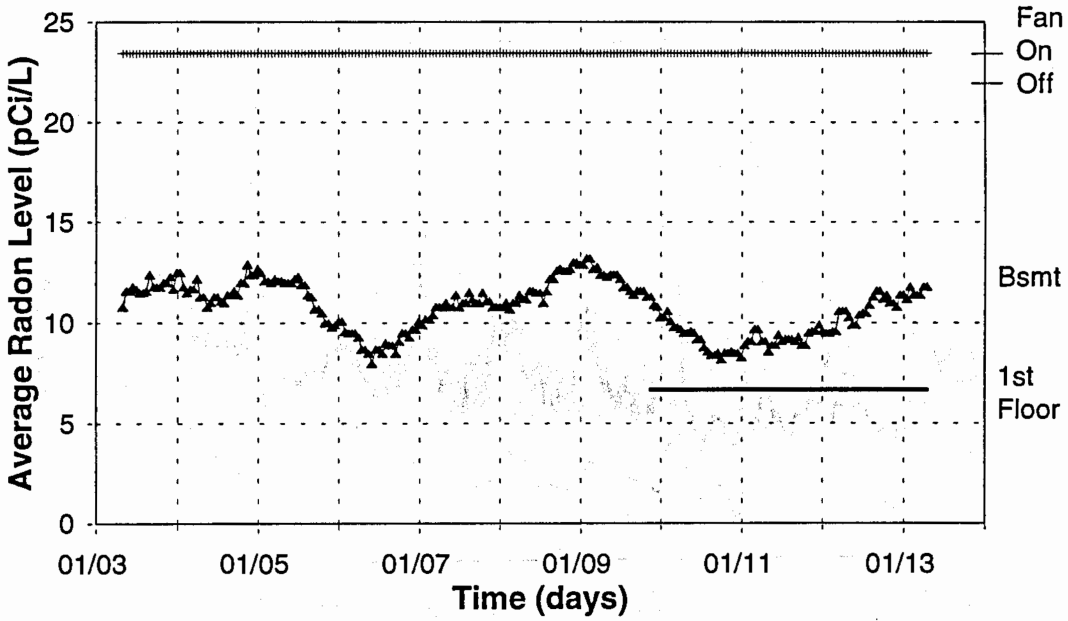


Figure 35. Vermont temperature/radon-trigger, period 3 fan and radon data

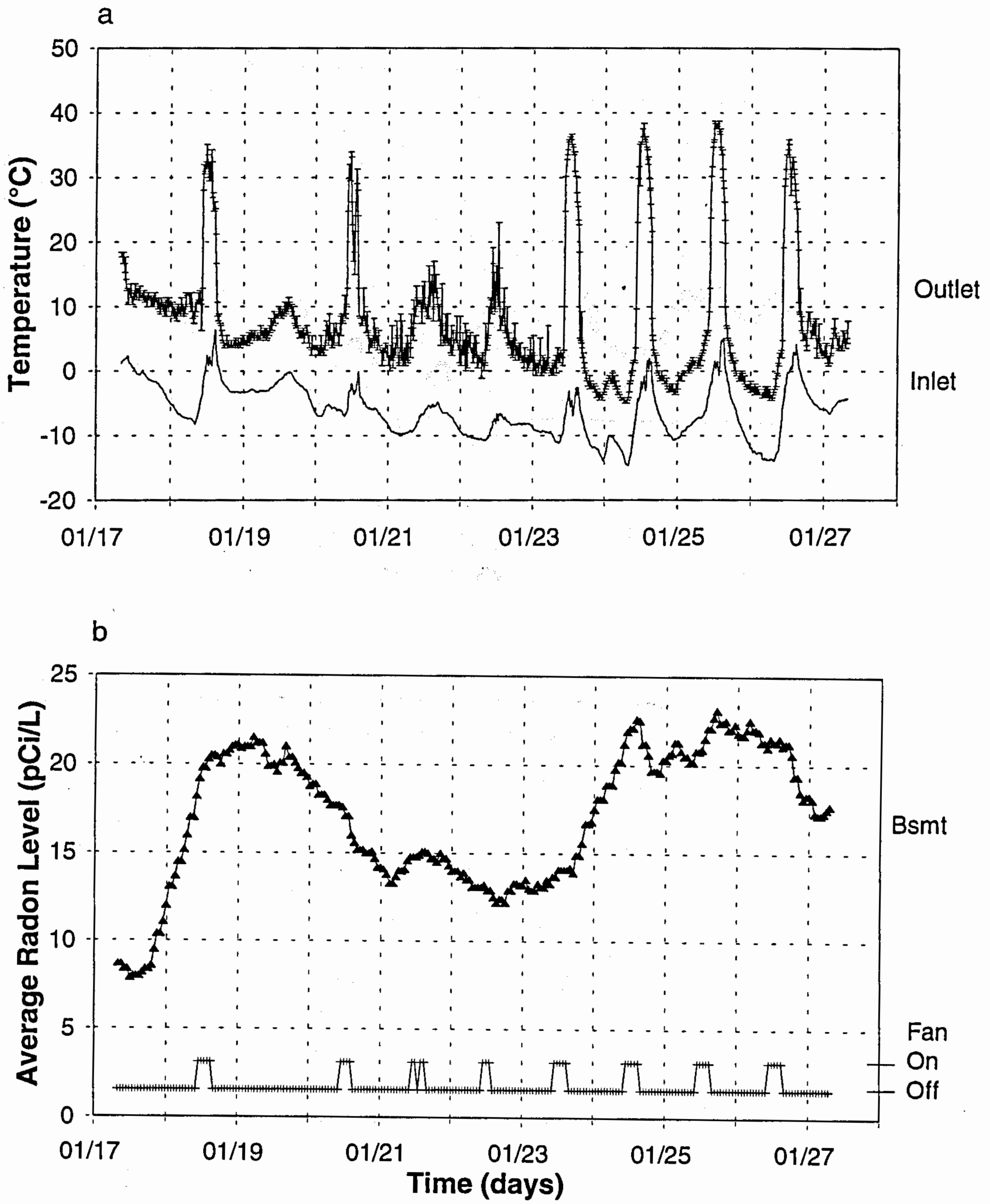


Figure 36. Vermont temperature-trigger, period 4:
(a) temperatures; (b) fan and radon data

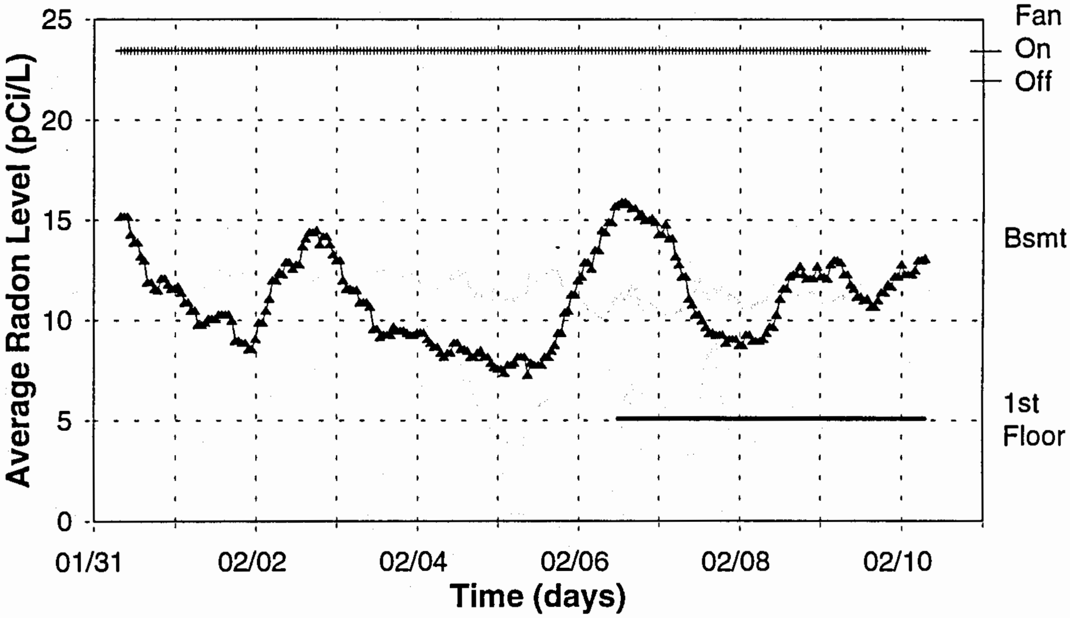


Figure 37. Vermont temperature/radon-trigger (6.0 pCi/L), period 5 fan and radon data

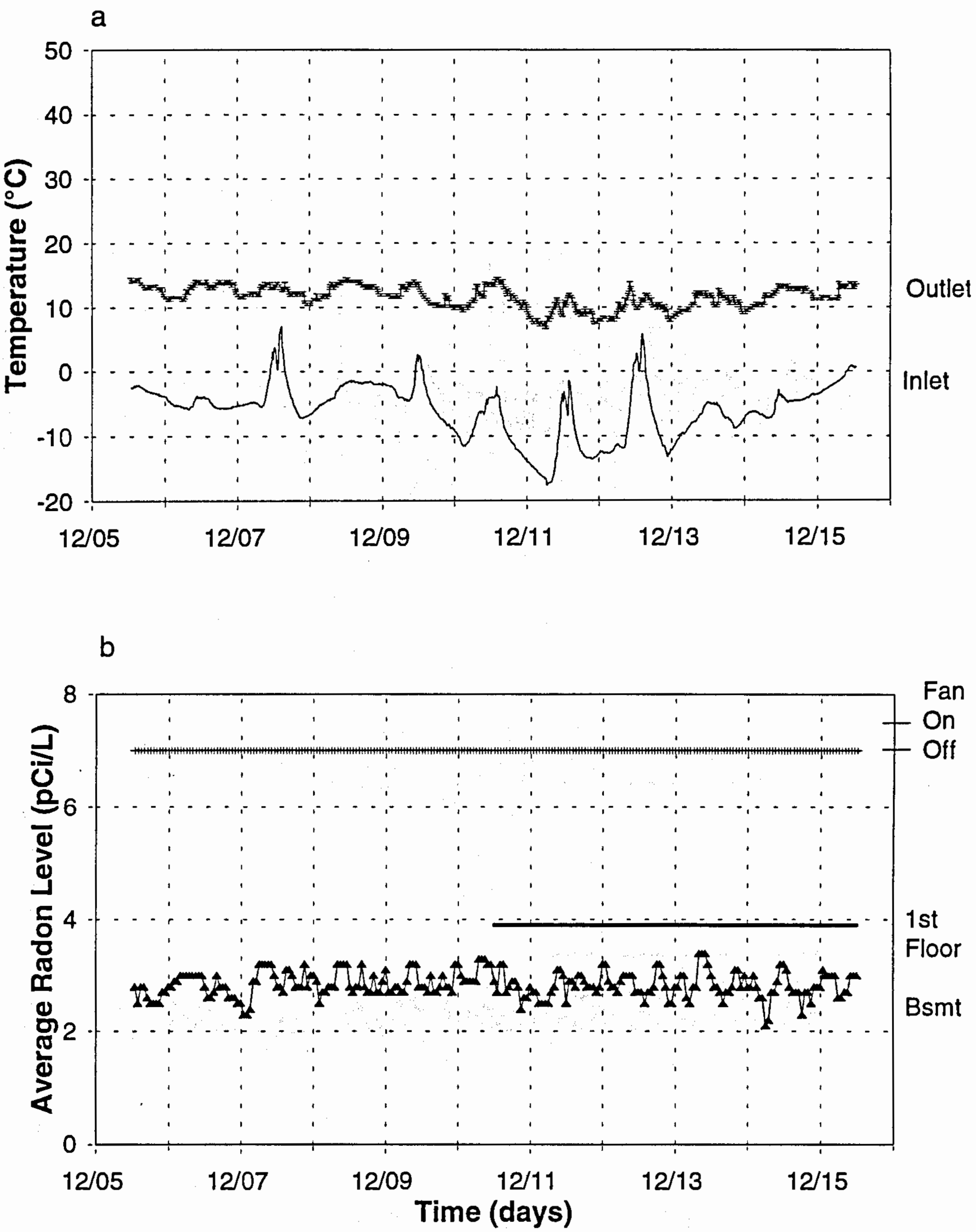


Figure 38. Washington closed house, period 1:
(a) temperatures; (b) fan and radon data

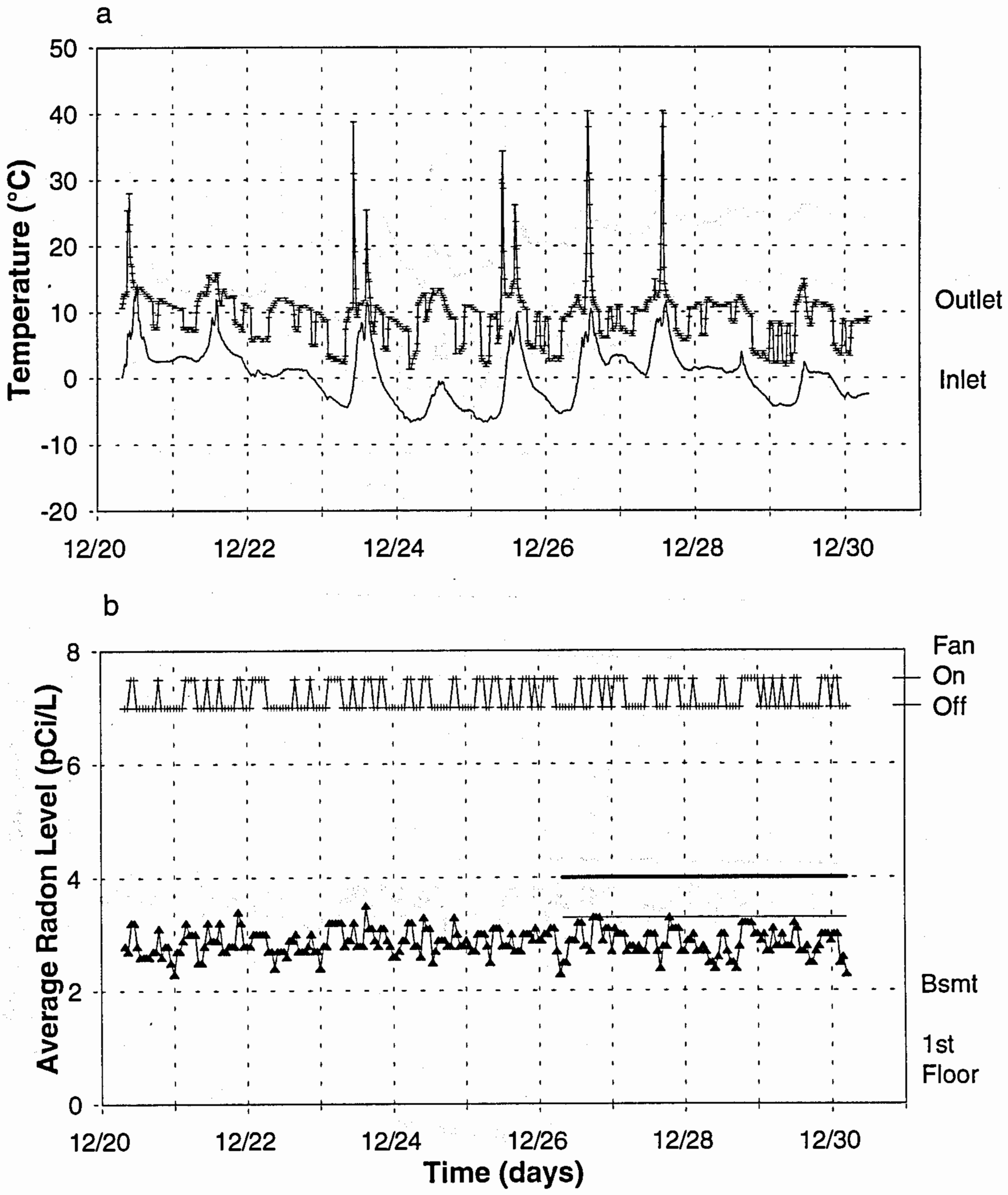


Figure 39. Washington radon-trigger, period 2:
(a) temperatures; (b) fan and radon data

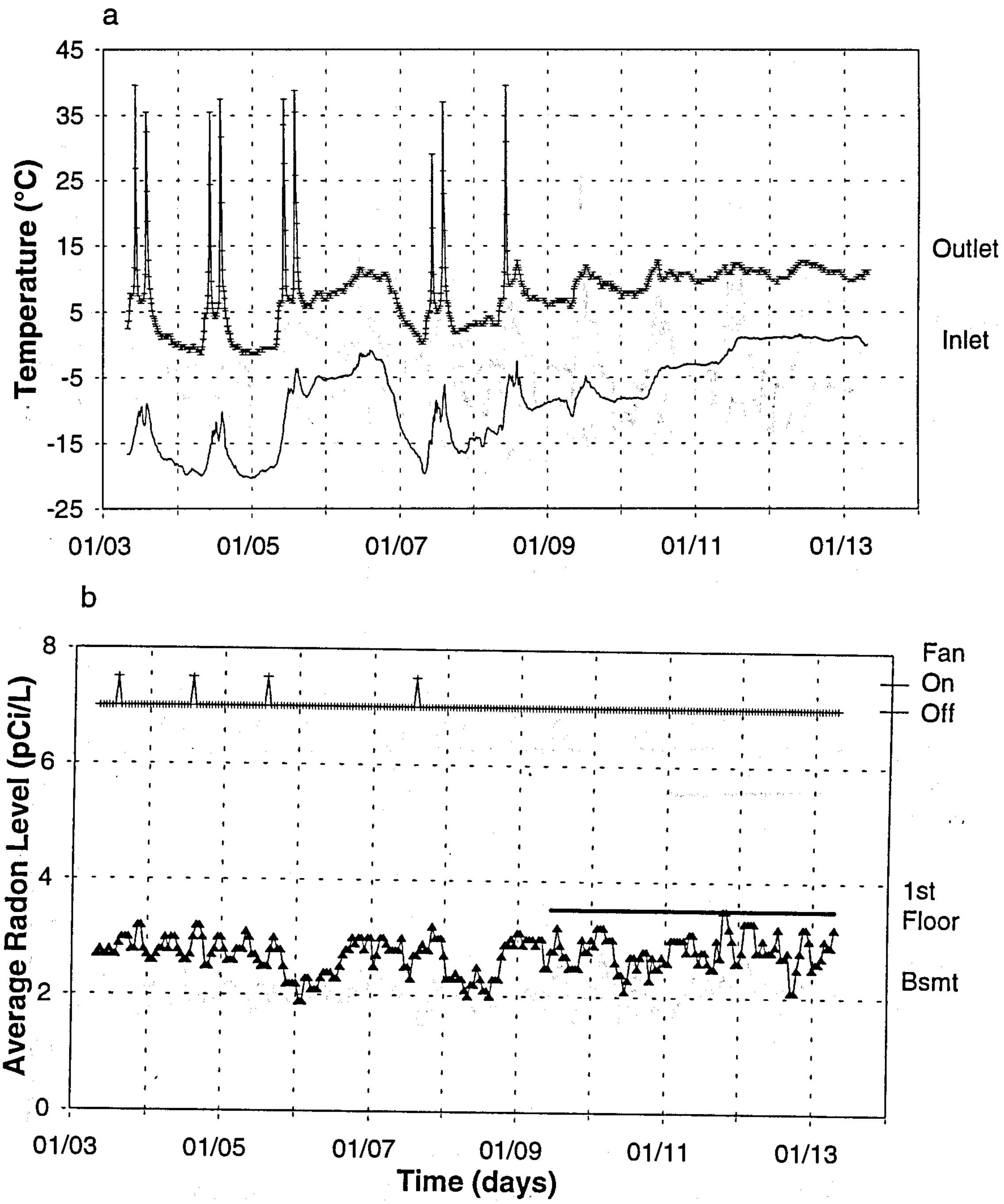


Figure 40. Washington temperature-trigger, period 3: (a) temperatures; (b) fan and radon data

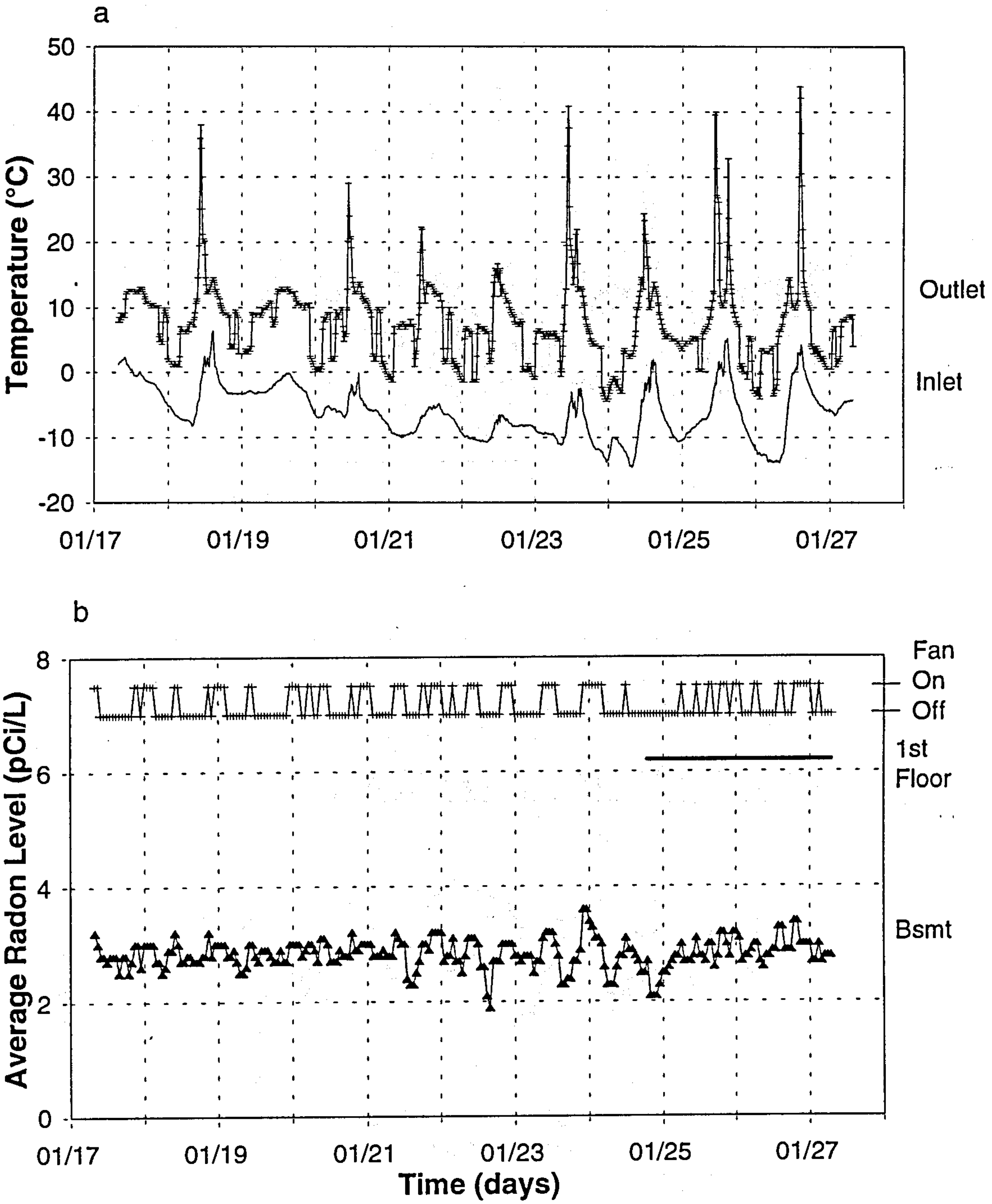


Figure 41. Washington temperature/radon-trigger, period 4: (a) temperatures; (b) fan and radon data

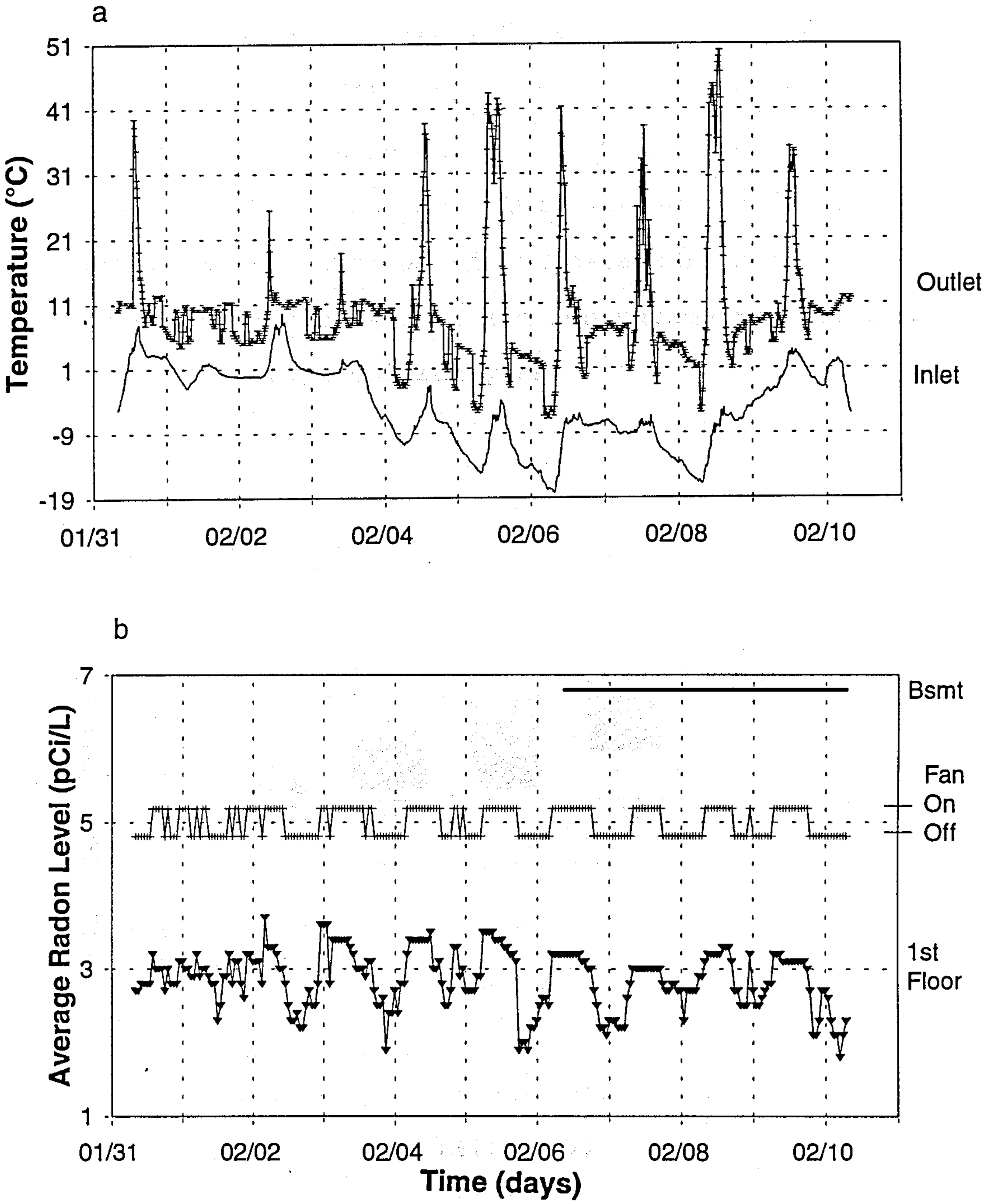


Figure 42. Washington temperature/radon-trigger (MTL Radon Alarm upstairs), period 5: (a) temperatures; (b) fan and radon data

Test Period Averages

Results of Kruskal-Wallis one-way analysis of variance on ranks and Dunn's pairwise multiple comparison procedures conducted with Sigma Stat for each house's test period radon data are included in Appendix G and shown graphically in Figures 43-48. Normality and equal variance tests failed for every data set, indicating the data were not normally distributed, so median values and non-parametric methods were used for statistical analyses.

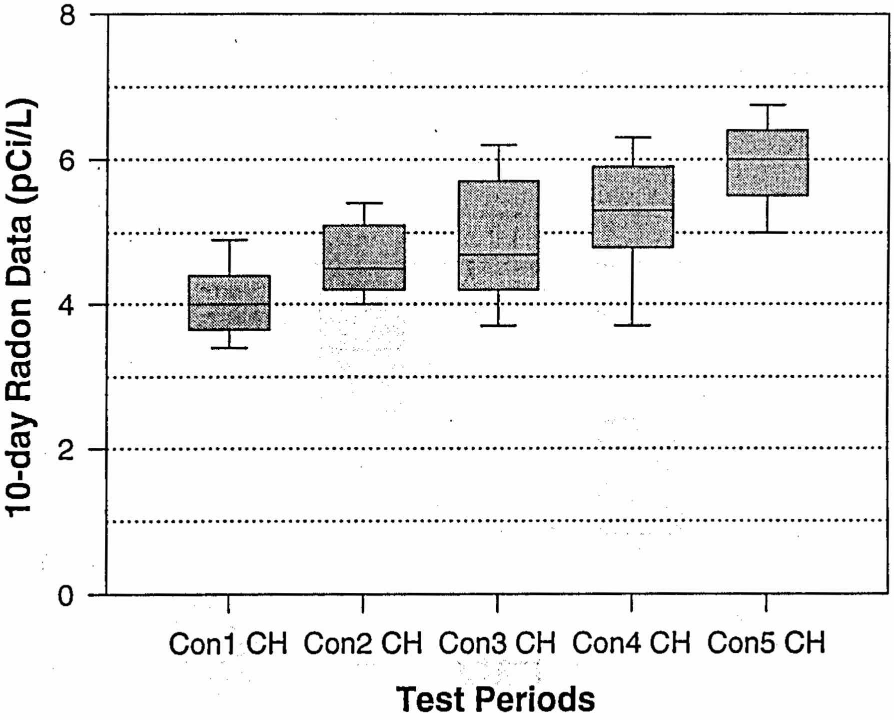


Figure 43. Variance of radon concentrations at Control with box extents indicating 25th and 75th percentiles of data; lines inside marking 50th percentiles; and capped bars indicating 10th and 90th percentiles. Bars with the same letter are not significantly different ($p < 0.05$)

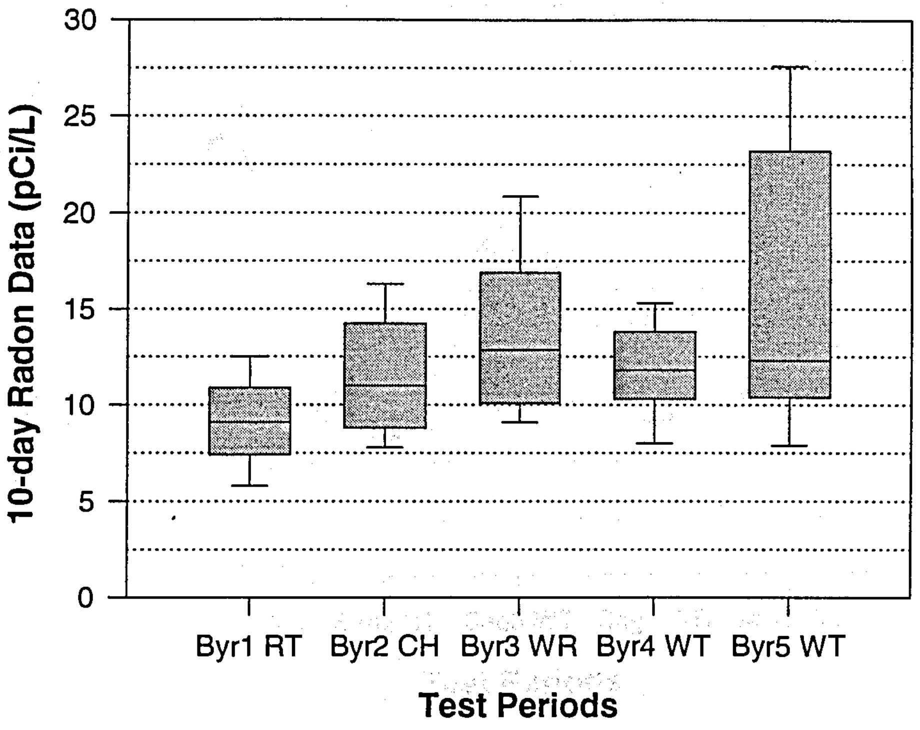


Figure 44. Variance of radon data at Byron (see Fig. 43)

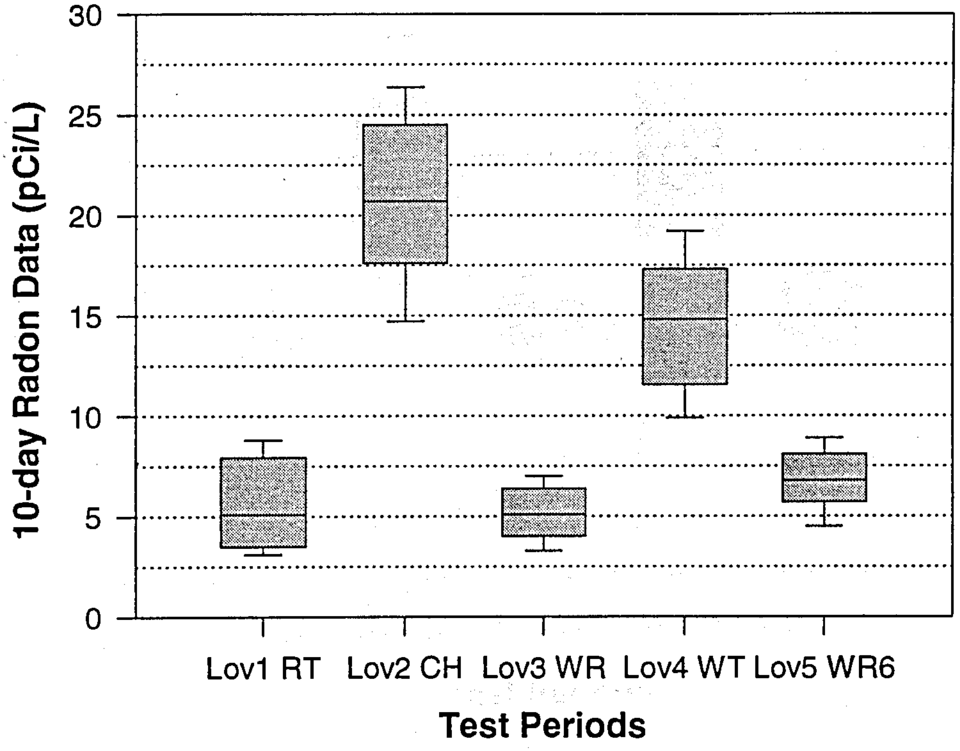


Figure 45. Variance of radon data at Lovejoy (see Fig. 43)

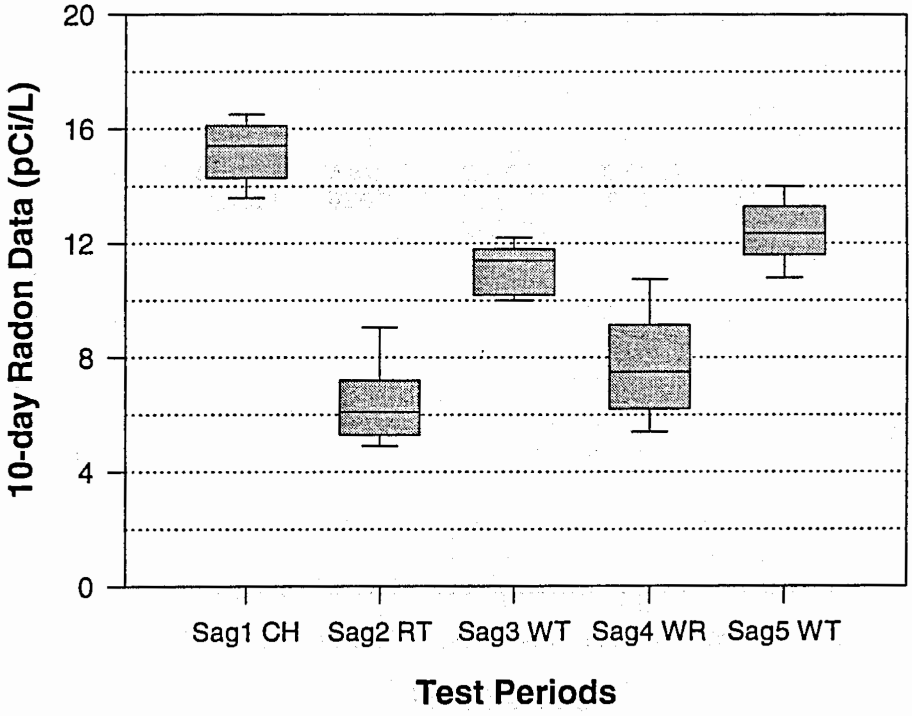


Figure 46. Variance of radon data at Sager (see Fig. 43)

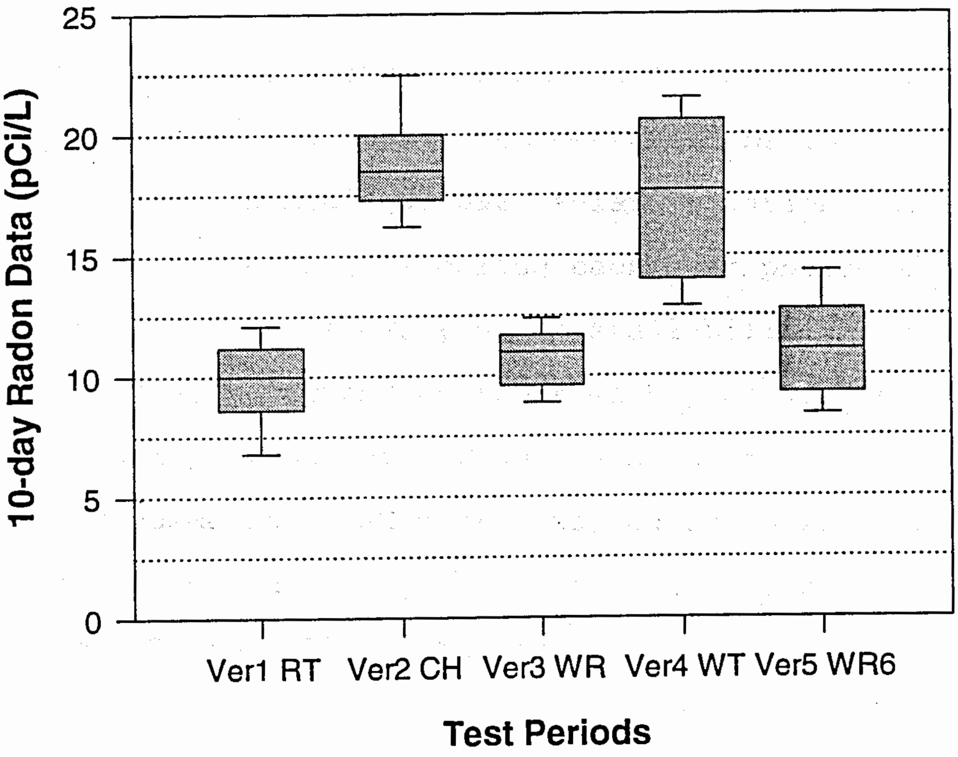


Figure 47. Variance of radon data at Vermont (see Fig. 43)

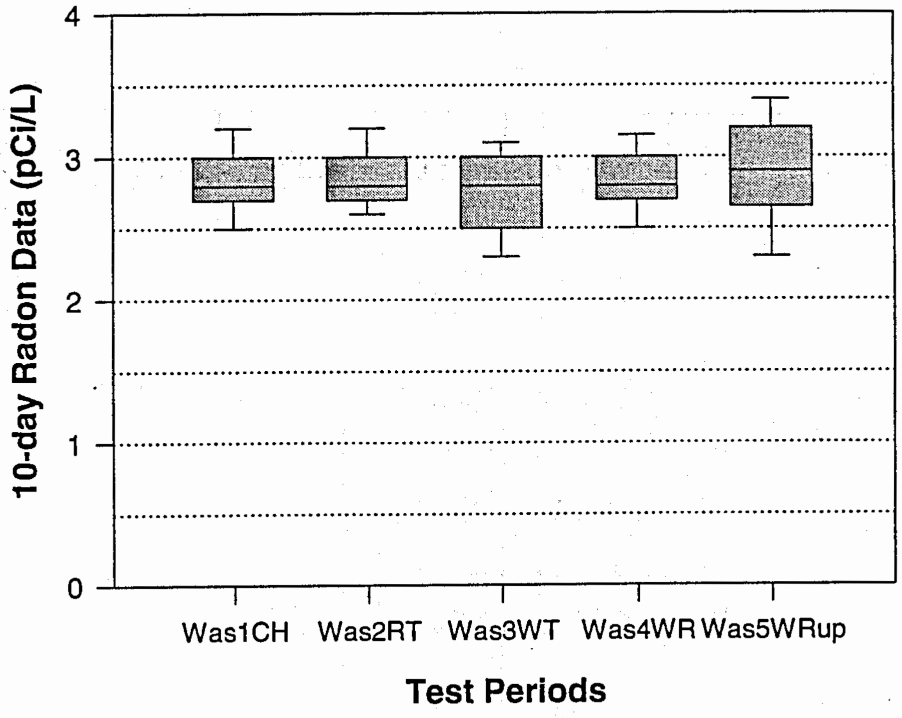


Figure 48. Variance of radon data at Washington
(see Fig. 43)

Time-weighted average radon concentrations, fan operation, inlet and outlet temperatures, basement pressure differentials, natural gas use, solar radiation, and heating degree days for each site during each test period are listed in Table 11. Average daily solar availability measured at Sager and heating demand as reported by the National Weather Service during each test period are also shown in Figure 49. Figure 50 summarizes radon results, adjusted with correction factors determined during post-research calibration testing (see Table 7) for all six houses.

Table 11. Test Period Data Summary

Test Period	Test Mode*	Bsmt	1st Flr	2nd Flr	SRRS Fan (% on)	Inlet		Outlet		Difference	House Pressure (Pa)	Natural Gas (ft^3/day)	Solar Rad. (W/m^2)	Heating Index (HDD/day)
		Radon (pCi/L)				Temperature (°C), RH (%)								
CONTROL														
1	CH	4.1	1.3	-	-	-5.9		-		-		7.2		46.6
2	CH	4.6	1.2	1.4	-	0.3		-		-		5.9		32.2
3	CH	4.9	-	-	-	-8.1		-		-		8.1		49.7
4	CH	5.2	-	-	-	-6.0		-		-		5.3		46.1
5	CH	6.0	-	-	-	-4.6		-		-		6.3		44.6
BYRON														
1	RT	9.2	6.1	6.6	100%	-5.9		3.1		9.0		4.5		46.6
2	CH	11.6	-	-	0%	0.5		22.4		-		4.0		32.2
3	WR	13.9	3.9	-	100%	-8.1		7.5		15.6		5.4		49.7
4	WT	12.1	6.1	-	18%	-6.2		7.3		13.5		5.0		46.1
5	WT timer	15.7	7.7	-	13%	-4.6		-		-		4.7		44.6
LOVEJOY														
1	RT	5.7	3.0	-	93%	-5.4		1.7	52.7%	7.1	-1.7	4.0	83.0	46.6
2	CH	20.9	9.4	-	0%	1.4		-	-	-	-2.7	4.0	70.6	32.2
3	WR	5.3	3.0	-	93%	-7.1		-1.1	38.5%	6.0	-2.5	6.3	106.2	49.7
4	WT	14.5	6.6	-	14%	-4.5		9.0	23.2%	13.5	-2.8	5.7	124.8	46.1
5	WR6	6.8	3.0	-	75%	-3.0		4.5	33.2%	7.5	-1.7	5.5	112.9	44.6
SAGER														
1	CH	14.6	12.6	-	0%	-5.9		22.3	35.4%	-	-3.4	4.7	79.6	46.6
2	RT	6.4	5.6	-	99%	0.3	63.1%	7.3	29.4%	7.0	-2.5	3.6	73.5	32.2
3	WT	10.7	8.1	-	14%	-8.1		3.6	42.0%	11.7	-3.8	4.5	93.5	49.7
4	WR	7.8	5.4	-	99%	-6.0		2.9	52.0%	8.9	-3	4.3	110.1	46.1
5	WT timer	12.4	8.0	-	10%	-4.6		19.1	29.8%	23.7	-3.6	4.3	102.3	44.6
VERMONT														
1	RT	9.8	5.0	-	100%	-5.9		4.3		10.2		3.8		46.6
2	CH	18.9	-	-	0%	0.5		21.5		-		4.1		32.2
3	WR	10.8	6.7	-	100%	-8.1		-		-		5.8		49.7
4	WT	17.1	-	-	15%	-6.0		7.6		-		5.4		46.1
5	WR6	11.1	5.1	-	100%	-4.6		-		-		5.3		44.6
WASHINGTON														
1	CH	2.8	3.9	-	0%	-5.9		11.6		-		5.9		46.6
2	RT	2.9	4.0	3.3	37%	0.5		9.6		9.1		5.2		32.2
3	WT	2.7	3.5	-	2%	-8.1		7.8		15.9		7.5		49.7
4	WR	2.8	6.2	-	35%	-6.0		7.7		13.7		7.1		46.1
5	WRup	6.8	2.9	-	50%	-4.6		9.6		14.2		5.7		44.6

**CH = closed house; RT = radon-trigger at 3 pCi/L threshold; WT = winter temperature-trigger with 20°C setpoint; WR = winter temp/radon-trigger; timer = 3 min delay to prevent excess cycling; WR6 = 6 pCi/L threshold; WRup = radon monitor on 1st floor*

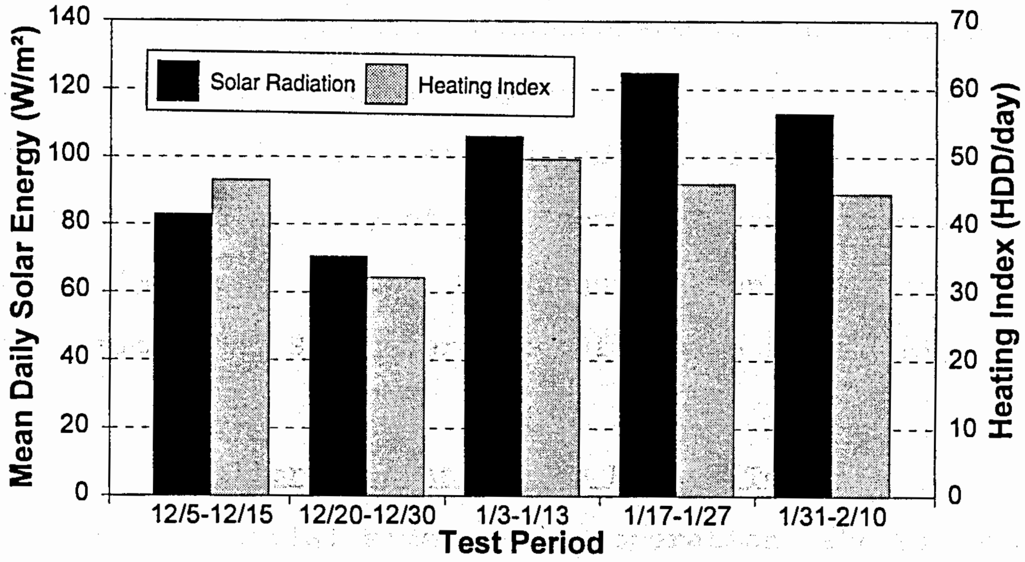


Figure 49. Solar insolation and heating degree days (HDD) for each test period

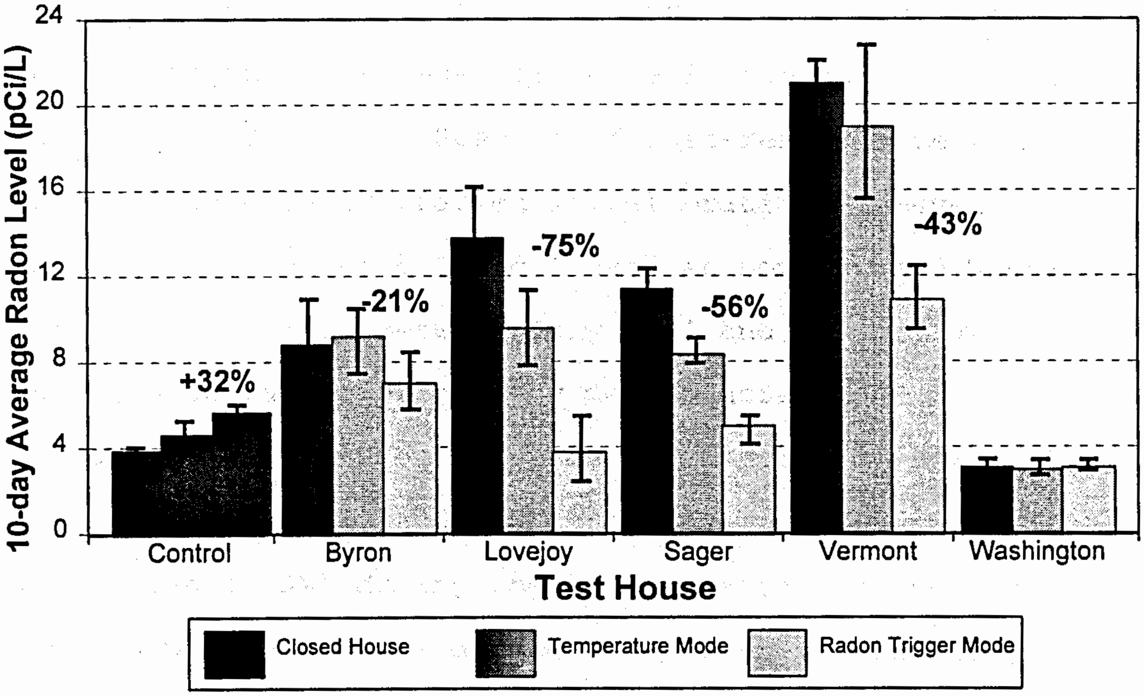


Figure 50. SRRS basement radon reduction compared to closed house conditions; capped bars indicate 25th and 75th percentiles of real-time data

VII DISCUSSION

This chapter focuses on interpretations of results presented in the previous chapter. The drift in radon monitor calibration is examined and accuracy of data is discussed. The ability of the "control" house to model external factors, effects of pressurization on radon infiltration, and SRRS energy benefits are also analyzed.

Calibration and Radon Mailer Tests

Based on initial side-by-side operation, the six MTL 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). Similar response among the units is illustrated in Figure 10 (p. 83) as the data generally move in the same directions on the three test days. Results of post-research testing revealed some deterioration in calibration, however, particularly in units C and F used at Lovejoy and Washington (Fig. 11, p. 83). Between July 1994 and March 1995 the standard deviation of monitor means increased from 0.2 to 2.3 pCi/L; calibration accuracy decreased from 94% to 81%.

The MTL Alarm used at Control (A) measured above the group mean (3.3%) during the pre-research test but was below the group mean (-6.8%) during the post-research test, while those used at Byron (B) and Lovejoy's basement (C) started out above the group mean (6.1% and 5.7%) and grew progressively higher (10.5% and 22.6%). Unit D used at Sager's basement started out lower than the group mean (-4.5%) and ended up considerably higher (9.2%); while those used at Vermont (E) and Washington (F) started out below (-4.1% and -8.3%) and dropped lower (-29.5% and -28.1%).

These comparisons indicate that the correction factors calculated to adjust units to the activated charcoal standard obtained during post-research calibration testing may not account for individual monitor shifts during the research. The units which increased between the pre- and post-research calibration tests (Byron, Lovejoy, and Sager) may have given relatively higher readings during the later test periods compared to the beginning; those which decreased between the calibration tests (Control, Vermont, and Washington) may have given higher readings during the first test periods compared to the later periods.

Charcoal mailer tests which duplicated radon monitor data during the first test period in December 1994 (Table 7, p. 82) indicate that the monitors at Control, Byron, Lovejoy first floor, Sager basement, and Vermont had higher averages relative to the charcoal testers during the time the mailers were open than during the post-research calibration test (March 1995); monitors at Sager first floor and Washington were lower relative to the charcoal testers than during the March calibration test. Most notably, the mailer result at

Vermont was 44% lower than its MTL Alarm radon mean; the mailer at Washington was 46% higher than its MTL Alarm mean.

Although AirChek reports that the charcoal test results are within 0.4 pCi/L of the "true" radon value, these large inconsistencies raise suspicions that the mailer data may not be reliable. Certainly the results of the two Enzone mailers used at Washington during the fourth and fifth test periods (6.2 and 6.8 pCi/L) appear to be well above the expected range for the site (3.3-4.1 pCi/L) based on AirChek mailers and monitor calibration tests.

Infiltration

SRRS fan air flow calculations shown in Table 9 (p. 85) indicate variations at the test houses 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.

When SRRS ventilation is added to natural infiltration, the amount of time a volume of air remains indoors is reduced, as shown in Figure 12 (p. 86). The effect of SRRS operation in adding air changes is dependent upon fan efficiency, house leakiness or natural infiltration, and envelope volume as shown in Table 10; for tighter houses SRRS ventilation is a larger portion of the structure's air exchange. Due to house sizes and fan air flow rates, SRRS operation adds between 0.20 ACH (Washington) and 0.47 ACH (Sager). The extra ventilation reduces Lovejoy's house air time constant from 5.7 H/AC with natural air infiltration to 2.3 hours combined with SRRS ventilation (59%) at Lovejoy, but only from 2.2 to 1.1 hours (51%) at Sager and from 1.6 to 1.1 hours (24%) at Washington. The calculation is shown for Control even though no SRRS was installed there to demonstrate the relative amount of air that a 75 CFM fan adds to a very leaky house is much smaller.

House leakiness appears to have the greatest effect on the ability of added SRRS ventilation to reduce the house air time constant. As the tightest house, Lovejoy's SRRS shows the greatest 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.

Basement/outdoor pressure differential data at Lovejoy and Sager (Figures 23-32) 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. 27, p. 99) with pressures alternating between -3 and 0 Pa in response to fan status. Test period pressure means for both Lovejoy and Sager indicate that duration of fan operation affects overall house pressure as well (Fig. 51), at airtight houses more so than at leaky houses.

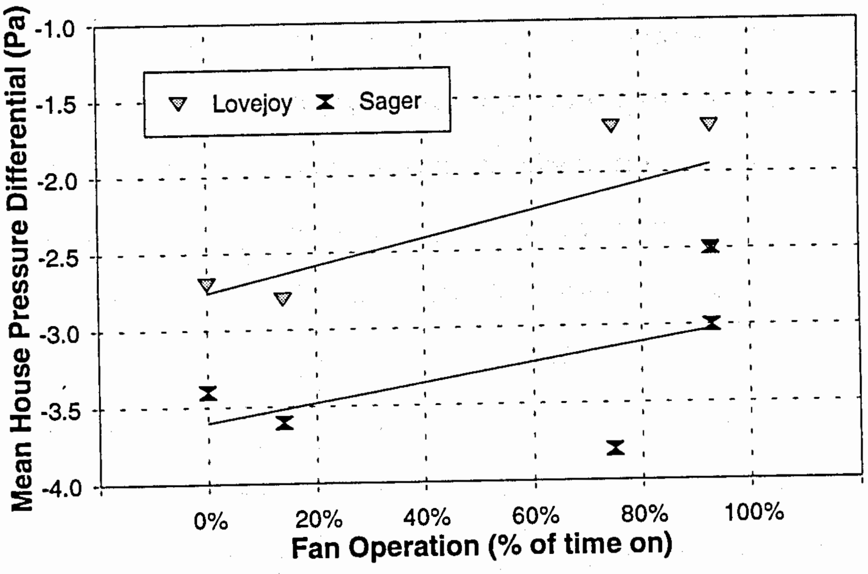


Figure 51. Effect of SRRS fan on house pressure differential

Test Period Data

As shown in Figures 13-17 (pp. 87-89), radon data for Control showed peaks and valleys spanning 1-2 days with an overall increase throughout the research period. The pairwise multiple comparison procedure indicated that each subsequent period had significantly higher radon levels, although the 25th and 75th percentile bars have some overlap with each. The first period is clearly significantly lower than the last period by this measure, as the 10th and 90th percentiles are entirely separate; however, these fluctuations are within the naturally occurring range for this house. The steady increase of Control's mean radon level over the entire research period indicates a rising baseline which may well affect the other homes in the study due to common weather variances and other external factors. Since Control's MTL unit 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 and exhibited relatively low radon levels, it does appear to serve as a good indicator of external driving forces of radon infiltration for houses in the area. The correlation of real-time radon trends at Control and test houses located 10 miles across town is graphically illustrated in Figures 52 and 53. A radon peak of more than a factor of three increase occurred on January 6 at Byron, closely coinciding

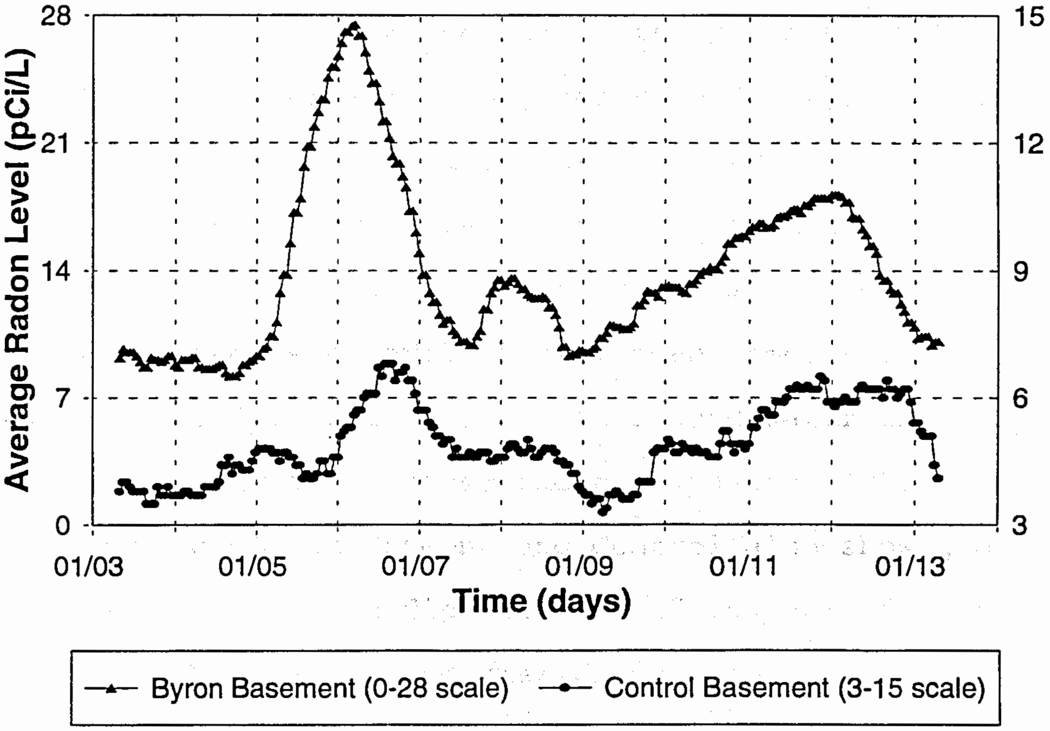


Figure 52. Byron and Control period 3 radon data

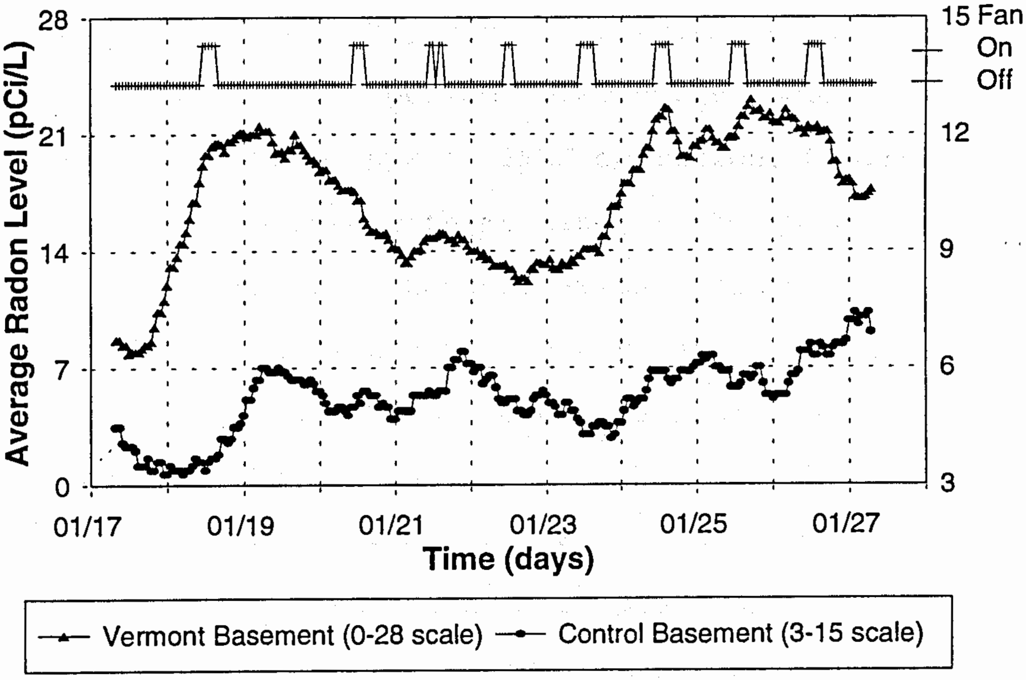


Figure 53. Vermont and Control period 4 radon data

with a large peak at Control and a storm front in the area, indicated by warmer inlet temperatures, decreased solar gain (Fig. 20), and a drop in atmospheric pressure shown on National Weather Service data sheets. Storm fronts presumably increase radon infiltration rates due to soil gas pressures being temporarily higher than atmospheric pressure; snowfall/rainfall and increased water table levels are also thought to increase radon (Lafavore 1987).

Radon levels at Vermont and Control also show good radon correlation with dips on Jan. 17 and upward trends immediately following, and smaller peaks on Jan. 21 (Fig. 53), even though during this period Vermont is affected by alternating fan operation (temperature-trigger operation). Radon accumulation at Control lags a few hours behind both Byron and Vermont, possibly due to differences in soil porosity. By the end of period 4 Vermont's radon is reduced by several consecutive days of SRRS operation; Control's radon increase coincided with melting of the snow cover.

Of all the SRRS test houses, Byron's radon level appears to be most affected by weather and external factors, as shown in Figure 54. Radon concentrations are corrected with monitor calibration factors and shown for each house as a percentage of the closed house mean level. Since closed house tests for the SRRS houses took place during the first and second periods, Control's radon levels were normalized to the mean of the first two periods.

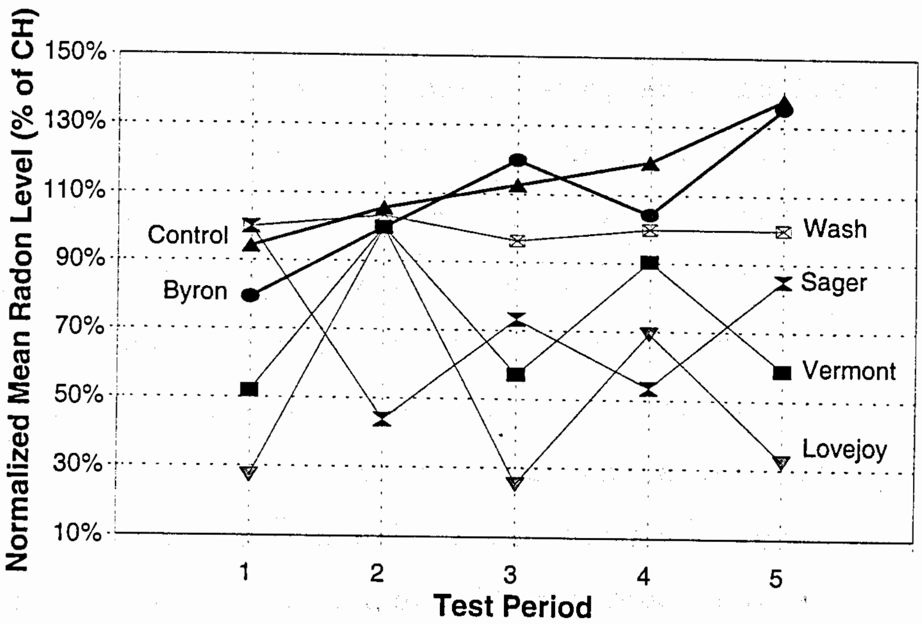


Figure 54. Radon variation over research period; test period means corrected with monitor calibration factors and normalized to closed house mean for each house (CH = 100%)

Byron was the only house which showed significantly lower radon levels during closed house testing than with subsequent test modes; calibration drift of its Radon Alarm may have inflated results during the latter test periods. Washington also showed little response to SRRS operation throughout the research period. Byron and Washington are the leakiest houses after Control (Fig. 12, p. 86), supporting the hypothesis that tighter houses respond better to increased basement ventilation. House leakiness was not found to be correlated to lower radon levels (Fig. 50, p. 120); since upper-story leaks contribute substantially to the stack effect and negative basement pressures, radon infiltration may be increased with higher air change rates.

The trends at Vermont and Lovejoy are similar to each other and alternate with Sager, as these two groups were operated in alternating modes over the test periods. These three tighter houses show considerable correlation between mean radon levels and duration of fan operation (Fig. 55). 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 accumulation rates even in closed house conditions, Washington's radon levels showed no correlation with SRRS operation.

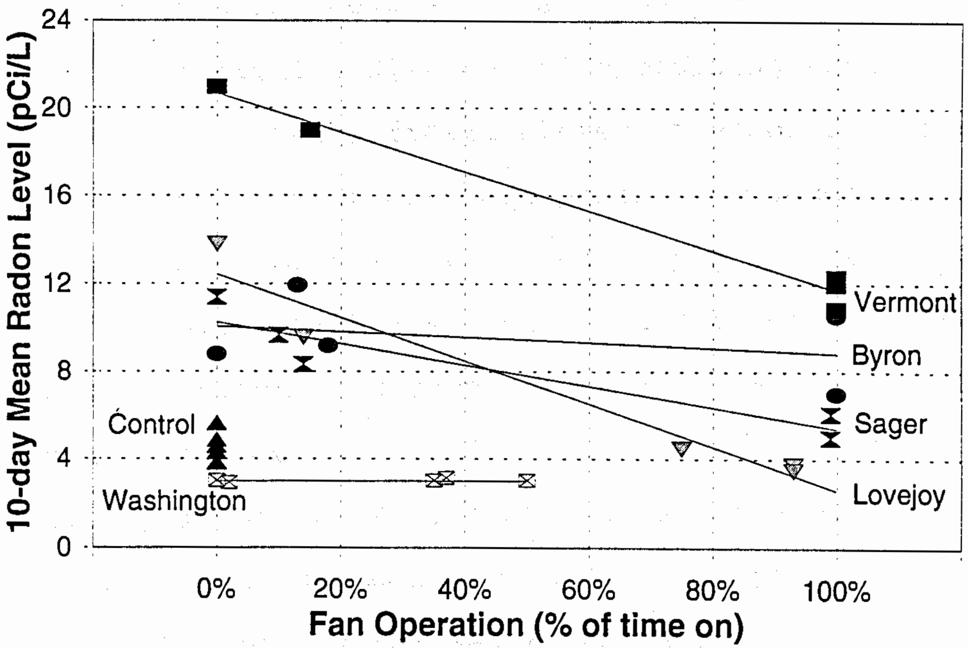


Figure 55. Effect of SRRS operation on basement radon (corrected with monitor calibration factors); lines show linear regression for each house

Energy and Cost Analyses

Temperature normals based on data from 1951-1980 show Iowa as having an average annual temperature of 8.9°C (48°F): -5.8°C in the winter, 8.8°C in the spring, 22.2°C in the summer, and 10.4°C in the fall (Gale 1983). Iowa has an average 6943 heating degree days annually: a total of 3912 heating degree days in the winter months (average of 43 per day); 1630 in the spring (18/day); 43 in the summer (0.5/day); and 1358 (15/day) in the fall (Gale 1983). Temperatures experienced during the research period were near the average (32-50 HDD/day) for Iowa for these months.

Outdoor temperatures appear to be inversely correlated to solar insolation (Fig. 49, p. 120), with the coldest test periods also having the greatest amount of solar radiation available. This is presumably due 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 solar collectors configured in the SRRS manner may achieve higher efficiencies than may be apparent by seasonal sunlight and temperature averages as larger solar gains may occur on colder days.

Solar gain at the SRRS test houses was affected not only by cloudiness and weather conditions but by obstructions at each site; Sager and Washington had most apparent blockages during heating intervals (see Fig. 34-37, 44-47). Sager's panel was shaded for a short period each day due to a deciduous tree trunk in the front yard; extensive shading by a neighboring house occurred at Washington during the shortest days of the year. A large coniferous tree to the southeast of Vermont's panel had less effect in reducing solar gain as it is cleared early in the day, and a deciduous tree at Lovejoy appeared to have little effect during this wintertime study.

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. As shown in Figures 23-48, SRRS outlet temperatures were always noticeably augmented over inlet temperatures presumably 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 35-40°C, with gains of up to 55°C occurring at Byron and Washington (see Figs. 21 and 42). Although substantial amounts of cold air was 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.

VIII CONCLUSIONS AND RECOMMENDATIONS

This chapter summarizes findings of the current study and discusses implications for system design improvements and applicability at additional homes. The SRRS was found to achieve significant radon reductions in all test houses with elevated levels; three of the five were maintained below the EPA action guideline during 10-day test periods. Radon levels were 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.

SRRS radon reduction efficiency was found to be related to both the duration of system operation and dwelling leakiness; 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 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 largest reduction was seen at Lovejoy, which employs no combustion appliances and had the only mitigation with sump pump pit sealing, of 73% in the basement and 68% on the first floor. 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); and reduced first floor levels at Vermont (5.0 pCi/L) and Sager (5.6 pCi/L) came close to the guideline.

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 from soil is dependent on its composition and condition, which may not be known, 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 radon industry.

These benefits suggest more homeowners may be likely to install radon mitigation systems as well as solar collectors, and be less likely to discontinue their operation.

Design Improvements

While providing a great deal of information about SRRS operation and effectiveness, this study raised new questions and additional possibilities to explore. For instance, since the MTL Radon Alarms output a radon value which is an average of the previous 22 hours, the lag time between the start of an upward radon trend and the electrical activation of the SRRS fan may be a limiting factor. Timer-based SRRS operation at Lovejoy has shown reductions similar to those during radon-trigger operation with fewer fan hours, suggesting a possible levelling-off effect at a minimum radon concentration.

The simpler timer-activation may preempt radon fluctuations with consistent ventilation, and it can also limit fan operation with undesirable outlet temperatures to periods less noticeable to occupants while still capturing heat gain. However, duration of system operation may be over-estimated and timers do not accommodate varying weather conditions. Custom-developed radon-trigger and temperature-trigger control units enable more sophisticated operational modes, and the modification of locating the Radon Alarm on the first floor, to activate the SRRS fan based on living space radon levels, may provide a tighter mitigation control. This may give homeowners a greater opportunity to monitor operational effectiveness, and it may be required for homes such as Washington that sometimes have higher radon levels upstairs than in the basement.

The customized electronic 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 an LED display 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 energy 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; the control unit and MTL Radon Alarm could easily be configured to run on DC. While adding significant costs, heat recovery devices could be incorporated with the SRRS to enhance energy benefits; solar water heating and heat storage systems would greatly improve the system's heat gain capacity; and the addition of active solar cooling to the system may prove beneficial.

As discussed above, upper-story insulation should be added and seals around upstairs windows and doors as well as basement windows and stairway doors be tightened with weather stripping and caulking at the leakier homes; ensuring air-tight doors between the 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 may also be minimized by sealing return furnace ductwork, creating a direct outdoor air supply for the furnace intake, and replacing combustion appliances with electric. Hinged dampers for the SRRS outlet should be installed to prevent backdrafting of basement air outdoors during non-operation.

Although MTL 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 monitor readings to activated charcoal mailers. Monitors reading low may not activate the fan for enough time to lower radon concentrations to the desired level; those reading high may activate it for more hours than necessary and thus consume excessive energy. These problems can be avoided by adjusting the mitigation threshold according to a correction factor compared to mailer results.

Technology Transfer

The results presented in this study show that the Solar Radon Reduction System is effective in reducing indoor radon concentrations with energy savings. 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 leakiness. Energy benefits afforded by this pre-heating approach in both residential and industrial settings are likely to increase as OSHA ventilation guidelines become more stringent.

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 in cold seasons must be preheated with expensive fossil fuels. Even where radon is not a concern, installation of appropriately-sized SRRS 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 market study for the SRRS found that nearly two-thirds of northeast Iowa homeowners surveyed would prefer to install radon mitigation systems themselves as opposed to hiring professional contractors, indicating that a ready-made simple installation kit may best advance this type of radon mitigation approach. Additionally, 77% of those surveyed indicated that tax credits would favorably influence their radon mitigation purchase decision; state or federal renewable energy incentives are certainly needed for large-scale investments.

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 the 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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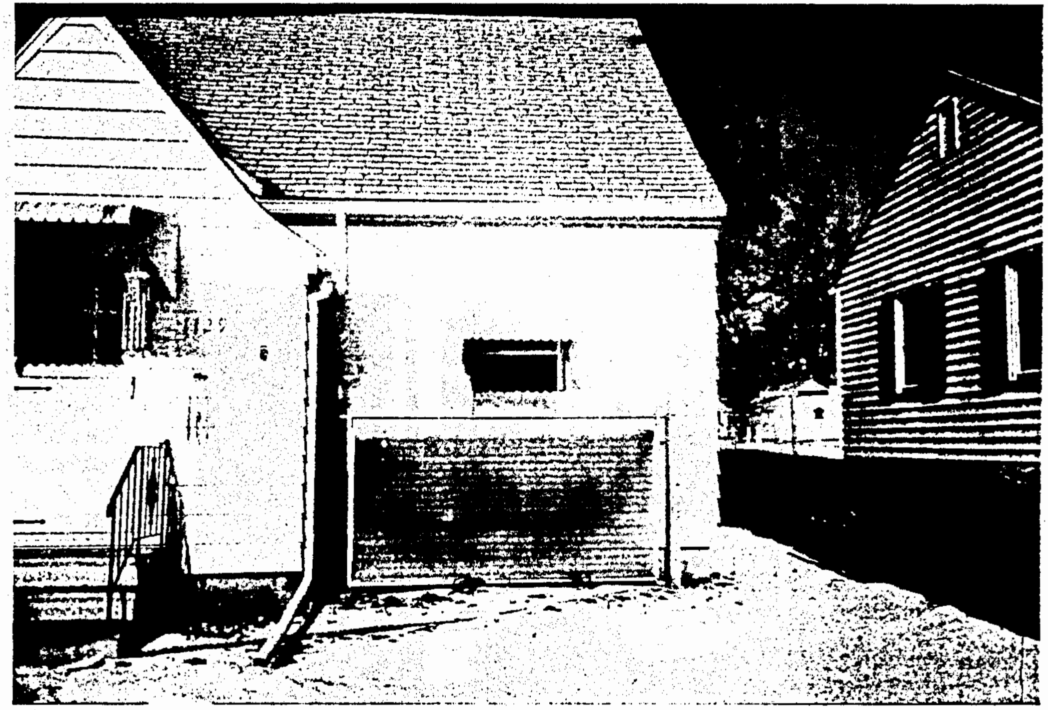
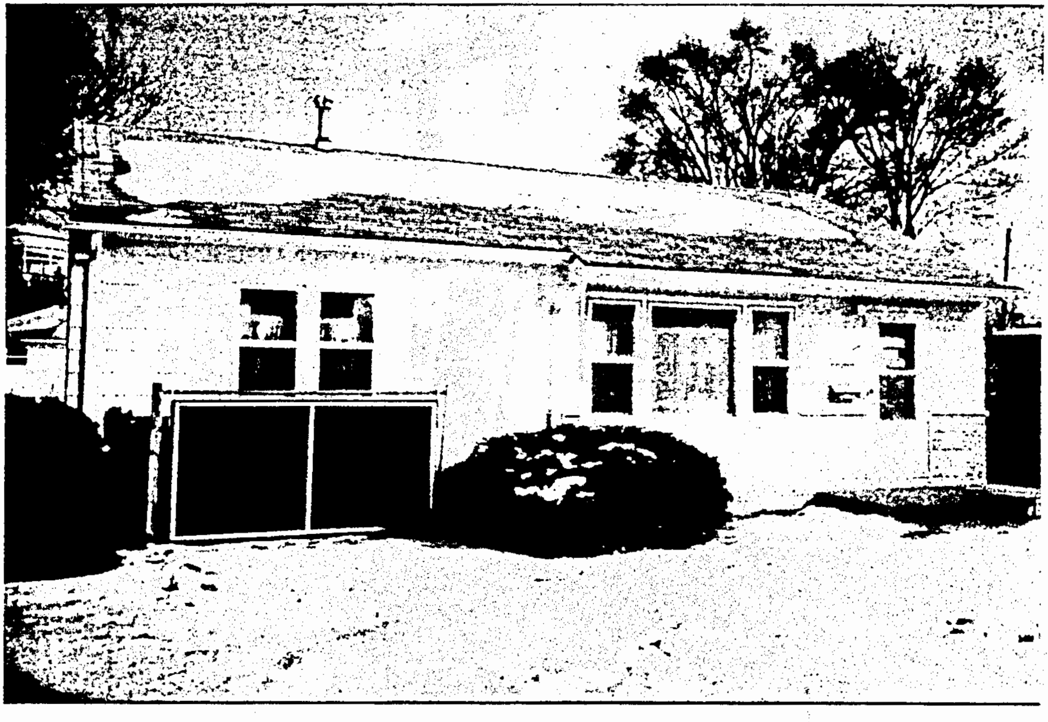
APPENDIX A: PHOTOGRAPHS OF SRRS TEST HOUSES

First installed SRRS and combination air/water collector constructed with recycled materials at test home North

Flush-mounted SRRS at second test home Lovejoy



SRRS mounted with 4″ × 4″ posts at test home Byron; panel outlet located above cold air inlet



Post-mounted SRRS at Sager; panel donated by G-S Energy

SRRS vertically-mounted with 2″ x 4″ beams at Vermont; duct passes from panel outlet at bottom through basement window

Vertically-angled SRRS at Washington; previously-used collector purchased at garage sale

APPENDIX B: SOLAR RADON REDUCTION SYSTEM PATENT

US005186160A

United States Patent [19]

Klein, II

[11] **Patent Number: 5,186,160**

[45] **Date of Patent: Feb. 16, 1993**

[54] **SOLAR RADON REDUCTION**

[76] Inventor: **Richard J. Klein, II**, 4028 North Ave., Waterloo, Iowa 50702

[21] Appl. No.: **750,987**

[22] Filed: **Aug. 28, 1991**

[51] Int. Cl.^{5} **F24J 2/04**

[52] U.S. Cl. **126/586**; 126/631; 126/616; 454/909

[58] Field of Search 454/233, 909; 126/427, 126/428

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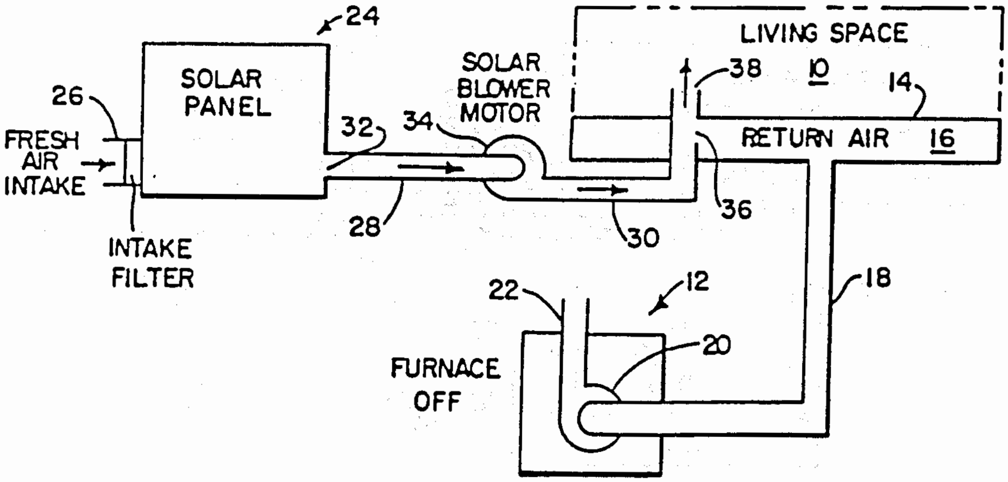
Primary Examiner—William E. Tapolcai

Attorney, Agent, or Firm—Andrus, Sceales, Starke & Sawall

[57] **ABSTRACT**

A supplementary heat and air supply system for a building includes a solar panel mounted to the exterior of the building, and a solar panel duct extending between the solar panel and the return air manifold of the building's conventional heating system. A fan or blower is positioned within the solar panel duct. The solar panel has a fresh air intake to provide fresh outdoor air to the interior of the solar panel. During daytime hours, when the temperature of air within the solar panel attains a predetermined level, the blower is operated to supply the heated air to the interior of the structure through the solar panel duct, with the heated air being supplied through the return air manifold. When the building's furnace operates, it draws air from the return air manifold, which also acts to draw air from the solar panel through the solar panel duct. The system acts to pressurize the building's interior during operation of the blower, to deter seepage of gases, such as radon, into the building's interior. When the blower is not operating and the furnace is operating, the furnace draws air from the solar panel along with the indoor air. This additionally reduces the amount of pressure drop in the building interior, to again deter seepage of gases into the building.

10 Claims, 1 Drawing Sheet



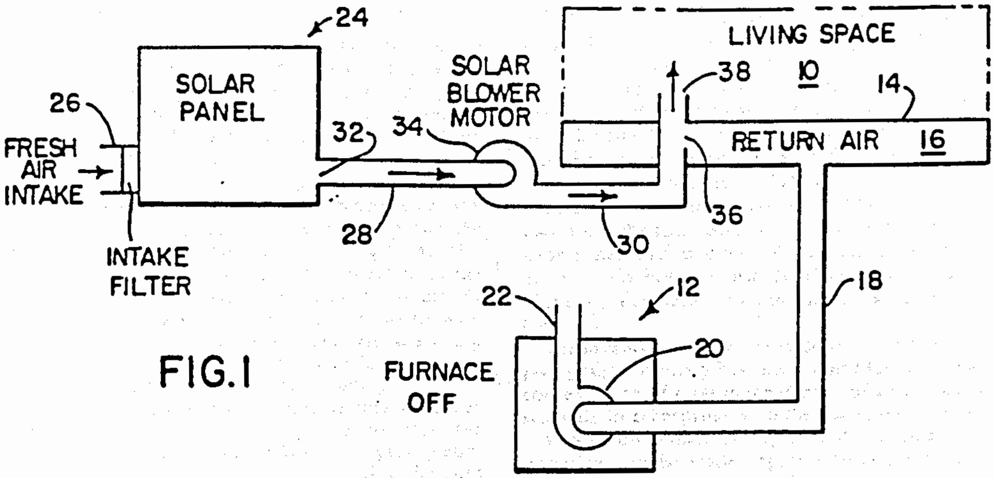


FIG.1

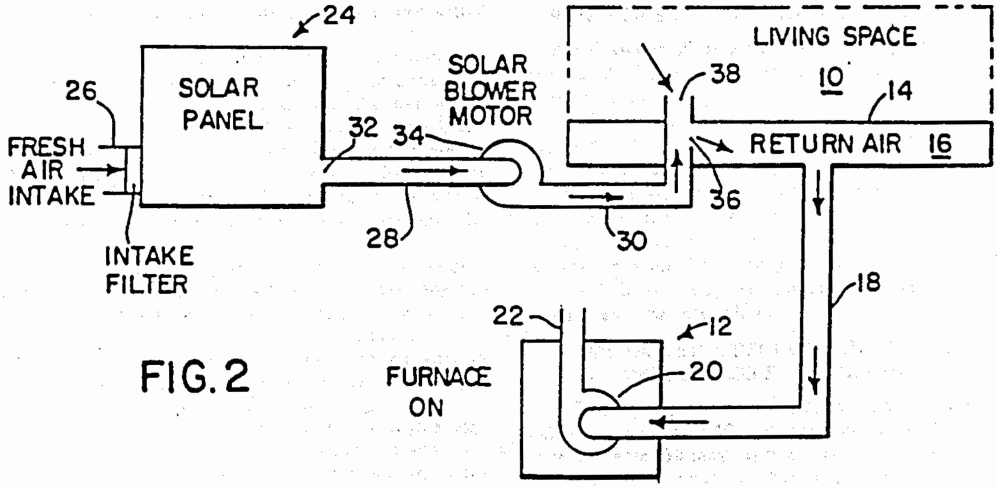


FIG.2

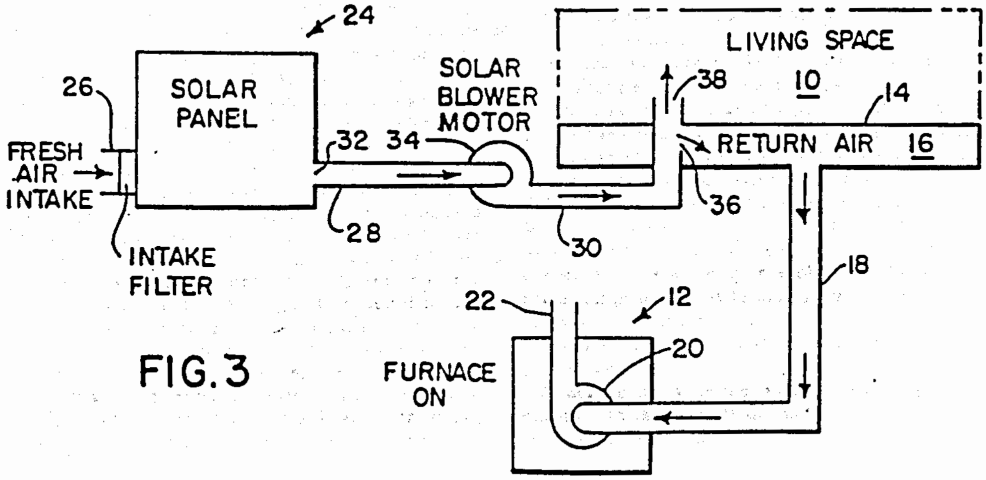


FIG.3

SOLAR RADON REDUCTION

BACKGROUND AND SUMMARY

This invention relates to a supplementary heating and air supply system, and more particularly to such a system which functions to pressurize or to prevent depressurization of, the interior of a structure and to reduce the concentration of any gases, such as radon, which may seep into the structure.

In heating the interior of a structure, such as a residential or commercial building, it is common to employ a forced air furnace, with duct work extending from the furnace to the various rooms of the building for supplying heated air under pressure during operation of the furnace. Such a system typically includes a return air system for returning air from the rooms to the furnace, which reheats the air and supplies such air to a living area within the building. The return air is supplied to the furnace from the interior of the building.

One problem with a conventional heating system as described is that it draws air for combustion from the interior of the building. Such indoor air typically contains more moisture than outdoor air during the cold weather heating season. In addition, drawing indoor air for combustion reduces the internal air pressure within the building.

In some geographical areas, it has been discovered and well documented that radon gas seeps into the basement of a building through cracks or the like in the foundation, basement walls, floor slab or the waste water discharge system. This problem is compounded when, during operation of the furnace, the pressure within the basement is reduced. Such reduction in pressure results in increased seepage of radon gas into the building's basement.

It is an object of the present invention to provide a supplementary heating and air supply system for use with a conventional heating system, to provide outdoor make-up air to the furnace for combustion during operation of the furnace. It is a further object of the invention to provide a system for reducing seepage of radon gas or the like into the basement of a building.

The invention is employed in connection with a conventional heating system including a furnace and a return air duct extending between the furnace and a return air inlet, which is in communication with the interior of the building. In accordance with the invention, a solar panel is mounted to the exterior of the building, and includes a fresh air intake for receiving air from the exterior of the building, and an outlet for discharging air from the solar panel. A solar panel duct is connected between the solar panel outlet and the return air duct, having a first end in communication with the solar panel outlet and a second end in communication with the return air duct adjacent the return air inlet. A blower is mounted in the solar panel duct. The blower is interconnected with a temperature-sensitive switch associated with the solar panel, such that operation of the blower is initiated when the temperature of air within the solar panel attains a predetermined level. Operation of the blower draws air from the solar panel and supplies such air under pressure through the solar panel duct to the return air duct. When the furnace is not operating, the air supplied by the blower passes through the solar panel duct and the return air inlet, into the interior of the building to provide heat thereto. Upon operation of the furnace, air is supplied to the furnace from the return air inlet. A portion of the return air comes from the room in which the return air inlet is located, and a portion comes from the outlet of the solar panel duct.

With the invention as summarized above, heated air is supplied to the building interior upon operation of the blower. Such supply of heated air not only heats the building interior, but also increases the air pressure in the interior of the building, due to air being supplied to the solar panel from outside the building. This acts to reduce seepage of radon, or other gases, into the building through the basement. During operation of the furnace, a portion of the return air is supplied to the furnace from the solar panel duct. Since the air from the solar panel duct is drawn from outside, it generally contains less moisture than the indoor air and is more efficiently combusted by the furnace along with the fuel.

The invention further contemplates a method of supplying supplementary heat and air, and for reducing the concentration of a gas in the interior of a building, substantially in accordance with the foregoing summary.

Various other features, objects and advantages of the invention will be made apparent from the following description taken together with the drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

The drawings illustrate the best mode presently contemplated of carrying out the invention.

In the drawings:

FIGS. 1, 2 and 3 are schematic representations of the supplementary heat and air supply and radon reduction system constructed according to the invention.

FIG. 1 shows the system with the furnace off during operation of the solar blower;

FIG. 2 shows the system with the furnace on when the solar blower is not operating; and

FIG. 3 shows the system during operation of both the furnace and the solar blower.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

In FIGS. 1-3, an interior room or living space of a building is shown at 10, it being understood that reference character 10 may represent any other space to be heated in the interior of a building or the like. A furnace, shown generally at 12, is located within the building, typically in the building's basement. However, furnace 12 may be in any other satisfactory location within the building.

A return air manifold 14 is provided in living space 10, defining an internal return air cavity 16. Return air manifold 14 may be in any location within living space 10, such as under the floor of the living space. A return air duct 18 extends between return air cavity 16 and an air supply plenum associated with furnace 12.

Furnace 12 is provided with a conventional blower 20 which, during operation of furnace 12, provides heated air to a hot air duct 22. As is known, duct 22 is connected to a series of branch ducts for supplying heated air generated by furnace 12 under pressure to the various rooms of the building.

The above-described components and operation are all well-known.

In accordance with the invention, a solar panel 24 is mounted to the exterior of the building within which living space 10 is located.

Solar panel 24 is of conventional construction, and is typically mounted to the roof of the building with a southerly exposure, to provide a maximum amount of solar energy for heating air within its internal cavity. A fresh air intake passage 26 is associated with solar panel 24, for supplying fresh outside air, from the exterior of the building, to the internal cavity of solar panel 24.

A solar panel duct, consisting of a first portion 28 and a second portion 30, is disposed between solar panel 24 and return air manifold 16. First portion 28 of the solar panel duct defines an inlet 32 in communication with an outlet formed in solar panel 24, such that first portion 28 of the solar panel duct communicates with the internal cavity of solar panel 24. A blower 34 is positioned between first portion 28 and second portion 30 of the solar panel duct. It is understood that blower 34 is schematically illustrated, and alternatively may take the form of a fan placed within the interior passage defined by the solar panel duct.

One end of second portion 30 of the solar panel duct is connected to the outlet of blower 34, so as to receive pressurized air supplied by blower 34 during its operation. The other end of second portion 30 of the solar panel duct is interconnected with return air manifold 14. This end of duct second portion 30 is provided with a first inlet/outlet opening 36 which communicates with the interior of return air manifold 14, and a second inlet/outlet opening 38 which is positioned exteriorly of return air manifold 14 and communicates directly with living space 10.

A temperature-sensitive switch (not shown) is interconnected between blower 34 and the internal cavity of solar panel 24. In this manner, blower 34 operates only when the temperature of air within the internal cavity of solar panel 24 attains a predetermined level, e.g. 110° F.

In operation, the above-described components function as follows.

Fresh air is supplied to the internal cavity of solar panel 24 through intake passage 26, with an intake filter acting to filter air prior to its supply to solar panel 24. When solar panel 24 is exposed to sunlight so as to heat air contained within its internal cavity, and the air temperature attains the predetermined level, blower 34 initiates operation to supply such heated air through first and second portions 28, 30 of the solar panel duct to inlet/outlet opening 38 of duct second portion 30 and into living space 10. This acts to heat living space 10 during daylight hours. In addition, the supply of heated air under pressure from blower 34 maintains living space 10, as well as the building's basement within which furnace 12 is located, under increased pressure, to deter entry of gases, such as radon, into the basement.

A system according to the invention, as shown in FIGS. 1-3, has been installed and it has been discovered that on many cold, sunny days during the winter, blower 34 operates continuously to supply heated air from solar panel 24 to living space 10 sufficient to heat the entire living space, without operation of furnace 12.

When blower 34 shuts off, such as during nighttime hours or cloudy days when the temperature of air within solar panel 24 is not high enough to begin operation of blower 34, operation of furnace 12 to supply heated air to the interior of the building results in air being drawn from return air manifold 16 through return air duct 18. The resulting generation of negative air pressure within return air manifold 16 draws cold outside air from solar panel 24 through the solar panel duct first and second portions 28, 30 and inlet/outlet opening 36 of duct second portion 30. The cold outdoor air is mixed with the interior air drawn into return air manifold 16, and is supplied through return air duct 18. The mixing of cold outdoor air with the warmer indoor air results in more efficient heating and combustion of the air-fuel mixture upon operation of furnace 12, due mainly to the lowered moisture content provided by the cold outdoor air through solar panel 24.

During this mode of operation, the amount of air drawn from the interior of the building for combustion by furnace 12 is reduced by the amount of make-up air drawn from solar panel 24. This decreases the amount by which interior air pressure is reduced during operation of furnace 12, again reducing the amount of gas, such as radon, which otherwise would be drawn into the building's basement upon operation of furnace 12.

During simultaneous operation of blower 34 and furnace 12, as illustrated in FIG. 3, heated air supplied by blower 34 is simultaneously discharged into living space 10 through inlet/outlet opening 38 of duct second portion 30, and to return air manifold 16 through inlet/outlet opening 36 of duct second portion 30. In this manner, some outside air is mixed with the interior air supplied through return air duct to furnace 12, while some heated outdoor air is supplied to living space 10. This acts both to decrease the pressure loss in the building interior during operation of furnace 12, and also to provide some heated air into living space 10.

It should be appreciated that the discharge of second portion 30 of the solar panel duct should feed directly into return air manifold 16 for the most efficient supply of heated air into living space 10, to increase efficiency of the system.

The foregoing description has referred primarily to a gas or oil fired heating system. It is understood, however, that the system of the invention may also be advantageously used with an electric heating system or any other type of heating system.

The system of the invention can be installed for an extremely low cost, in that very few components are needed, and the necessary components can be easily installed. The only moving parts in the system are provided by blower 34, which is a very low maintenance piece of equipment.

The system provides no net increase in operating costs, even though on many days blower 34 may operate continuously during the day. This is mainly because blower 34 may take the form of a relatively small fan, requiring low amounts of power to operate. It has been found that, on average, the temperature of the building's interior can be maintained at a higher level during daytime hours, and that on average furnace 12 will not begin operation until the later evening hours.

In addition, the home in which the system of the invention was installed had a radon concentration of 8.8 pci/l, recorded over a five-day period prior to installation of the system. After installation of the system, a radon concentration of 2.5 pci/l was recorded for a six-day period, resulting in a net 72% reduction in radon level.

As can be appreciated, the invention performs two purposes very well, namely utilizing solar energy to conserve fossil fuel, and acting to reduce levels of radon in the interior of a building.

Various alternatives and embodiments are contemplated as being within the scope of the following claims particularly pointing out and distinctly claiming the subject matter regarded as the invention.

I claim:

1. A supplementary heating and air supply system for use with a conventional heating system including a furnace and a return air duct extending between the furnace and a return air inlet in communication with the interior of a structure, comprising:

a solar panel mounted to the exterior of the structure and including a fresh air intake for receiving air from the exterior of the structure, and an outlet for discharging air from the solar panel;

a solar panel duct having a first end in communication with the solar panel outlet and a second end in communication both directly with the interior of the structure and with the return duct adjacent to the return air inlet; and

a blower for drawing air from the solar panel and supplying such air through the solar panel duct either directly to the interior of the structure or to the return duct;

whereby operation of the blower supplies heated air from the solar panel through the solar panel duct either directly to the interior of the structure or to the return duct for discharge through the return air inlet into the interior of the structure, and whereby operation of the furnace draws air from the solar panel duct through the return duct.

2. The system of claim 1, wherein the solar panel duct has its second end in communication with a return air cavity provided at the return air inlet, and wherein the return air duct extends between the return air cavity and the furnace.

3. The system of claim 2, wherein the second end of the solar panel duct includes a first inlet/outlet opening located within the return air cavity and a second inlet/outlet opening located exteriorly of the return air cavity and within the interior of the structure.

4. The system of claim 1, wherein the blower is located within the solar panel duct between the solar panel and the return air inlet.

5. A method of supplying supplementary heat and air for a conventional heating system including a furnace and a return air duct extending between the furnace and a return air inlet in communication with the interior of a structure, comprising the steps of:

mounting a solar panel to the exterior of the structure, the solar panel having a fresh air intake for receiving air from the exterior of the structure, and further having an outlet for discharging air therefrom;

placing the solar panel outlet in communication either directly with the interior of the structure or with the return air duct adjacent the return air inlet;

supplying heated air under pressure from the solar panel outlet to the interior of the structure when the temperature of air within the solar panel reaches a predetermined level; or

drawing air from the solar panel through the return air duct upon operation of the furnace.

6. The method of claim 5, wherein the step of placing the solar panel outlet in communication with the return air duct adjacent to the return air inlet comprises connecting a solar panel duct having a first end in communication with the solar panel outlet and a second end in communication with the return air inlet.

7. The method of claim 6, wherein the return air inlet communicates through a return air cavity with the interior of the structure, and wherein the second end of the solar panel duct is provided with a first inlet/outlet opening and a second inlet/outlet opening, and is connected such that the first inlet/outlet opening is in communication with the return air cavity and the second inlet/outlet opening is located exteriorly of the return air cavity and communicates directly with the interior of the structure.

8. The method of claim 6, wherein the step of supplying heated air under pressure from the solar panel outlet comprises placing a blower within the solar panel duct and operating the blower to supply heated air to the second end of the solar panel duct.

9. The method of claim 8, wherein the step of operating the blower is carried out when the temperature of the air within the solar panel reaches a predetermined level.

10. A method of reducing the concentration of a gas, such as radon, in the interior of a structure having a heating system including a furnace and a return air duct extending between the furnace and a return air inlet in communication with the interior of the structure, comprising the steps of:

mounting a solar panel to the exterior of the structure, the solar panel having a first air intake for receiving air from the exterior of the structure, and further having an outlet for discharging air therefrom;

placing the solar panel outlet in communication either directly with the interior of the structure or with the return air duct adjacent to the return air inlet;

supplying heated air under pressure from the solar panel outlet to the interior of the structure when the temperature of air within the solar panel reaches a predetermined level, to thereby provide heated air to the interior of the structure and to pressurize the interior of the structure; or

drawing air from the solar panel through the return air duct upon operation of the furnace, to decrease the amount of air drawn by the furnace from the interior of the structure.

* * * * *

APPENDIX C: VOLUNTEER CONSENT FORM

RADON REDUCTION AND ENERGY SAVINGS THROUGH AN ORIGINAL SOLAR VENTILATION SYSTEM

Environmental Science M.S. Thesis Project
University of Northern Iowa

Heather Rhoads
Advisor: Dr. Peter Hoekje, Physics Department

INFORMED CONSENT FORM

Purpose

This project will evaluate the improvement of indoor air quality and energy savings achieved by an original solar ventilation system installed at test sites exhibiting elevated radon levels. A detailed assessment will be conducted of the extent that the Solar Radon Reduction System (SRRS) reduced radon levels and provided energy savings in the test homes, as well as how the system can be improved for homes or buildings with higher air pollution levels and for greater energy gain. The objective is to determine optimal operation modes under varying conditions for the system to most effectively reduce radon levels and other indoor air pollutants as well as to provide the highest net energy gain, with the overall goal of developing a viable, environmentally-appropriate approach to improving indoor air quality.

Procedures

Radon data will be collected in each test home using Radon Alert continuous radon monitors/data loggers in accordance with the Environmental Protection Agency's Radon Measurement Protocols, outlined in U.S. EPA Document #402-R-92-004, which include:

- Notifying occupants of the importance of proper testing conditions, which should include written instructions and careful explanation.
- Using a device listed by EPA's Radon Measurement Proficiency Program or certified by the state and following the manufacturer's instructions.
- Placing the device in the lowest level of the home suitable for occupancy. The test should be in a room used regularly, but not a kitchen, bathroom or laundry room.
- Conducting the test for a minimum of 48 hours under closed-house conditions, with all windows closed, all doors closed except for normal entry and exit, and no fans or other machines which bring in air from outside in operation.
- Maintaining closed-house conditions for at least 12 hours before beginning the test and for the entire test period for tests shorter than one week.
- Operating heating and cooling systems normally during the test, but for tests lasting less than one week only operating air conditioning units which recirculate interior air.
- Operating a radon reduction system, if any, at least 24 hours before beginning the test and during the entire test period.
- Not disturbing the test device at any time during the test and including methods to prevent or detect interference with testing conditions or with the testing device itself.
- Printing out reports which frequently record radon or decay product levels to detect unusual swings.

Blower-door tests will be conducted at each test site by Cedar Falls Utilities personnel to determine characteristics such as leakiness, air exchange rates, and pressure differentials. Installation of the SRRS will entail mounting a solar panel on or near a south-facing wall and inserting insulated ductwork through a 4"-diameter hole into the interior of the house.

Short-term evaluation of SRRS effectiveness for each test site will initially be conducted with the SRRS fan operating in the summertime free-cooling mode, when outdoor ambient temperatures drop below indoor temperatures, compared to the fan turning on when radon monitor levels exceed a preset limit. During the heating season, the system will be evaluated in both the radon monitor trigger-mode and the "solar-only" mode, when adequate solar energy is available to heat outside air above indoor temperatures. Data collected will include radon levels, solar radiation, inlet and outlet temperature and humidity, air speed, and indoor/outdoor pressure differentials at hourly intervals. The total heat gain resulting from solar panel operation will be calculated based on the cumulative volume of SRRS heated air introduced into the test homes.

Experimentation with design improvements and variations on SRRS operational modes will determine optimal system design for each house to most effectively reduce radon levels and other indoor air pollutants as well as to provide the highest net energy gain. The systems will be monitored and reconfigured to achieve radon levels of lower than the EPA action level of 4 pCi/L wherever possible.

Experimental Procedures

The most common method of radon mitigation is preventing radon from entering a building by pressurizing the contaminated space higher than that of the contiguous soil. A common approach is to pressurize the indoors with supply-air fans. A more costly method frequently employed is a sub-slab depressurization system, which applies suction beneath the foundation and vents this air above the roof, often requiring several holes to be drilled into the concrete slab. Sealing cracks and other openings in the foundation is a basic part of most approaches to radon reduction. However, the EPA does not recommend the use of sealing alone, as it has not been shown to lower radon levels significantly or consistently. The average cost for a contractor to lower radon levels in a home is about $1,000, although the repairs may range from $800 to $3,000. All commercially available ventilation/pressurization radon mitigation systems, including those equipped with air-to-air heat exchangers, operate with a net energy loss since they introduce below-ambient temperature indoors. Thus the common energy-intensive approaches to indoor air quality improvement often counteract steps to increase weatherization and energy conservation.

The patented Solar Radon Reduction System (SRRS) is a supplementary heating and air supply system comprised of a solar flat plate air panel equipped with mechanical ventilation, designed both to dilute and reduce the ability of radon gas to seep into the house. Through a variation of the conventional pressurization/increased ventilation radon remediation method, the SRRS prevents depressurization of the interior of a structure to reduce radon infiltration as well as decreases the concentration and thereby reduces the concentrations of radon and other indoor air pollutants present. During cold seasons, the SRRS introduces solar-heated outdoor air into the home, augmenting its existing heating system to produce a net energy gain. In the summer months, the system's blower can be used to ventilate the structure during the night and early morning to provide energy-free cooling when outdoor air temperatures drop below ambient indoor levels.

Risks or Discomforts

Participants will be asked to maintain closed-house conditions during radon monitoring, which may temporarily result in higher radon levels or other indoor air pollutants than under open-house conditions. Education regarding the long-term dangers of radon and knowledge of the homeowners' exposure levels may cause concern among participants. The installed Solar Radon Reduction System is not guaranteed to reduce radon levels.

The major health concern associated with radon exposure is an increased risk of contracting lung cancer; radon is a known carcinogen. The National Cancer Institute has singled out radon exposure as the leading cause of cancer among non-smokers, accounting for an estimated 7,000 to 30,000 deaths every year in the U.S. The EPA has set the radon concentration of 4 picocuries per liter of air (pCi/L) as its recommended "action level" for remediation, which is comparable to having more than 250 chest x-rays per year.

Risks anticipated during the proposed research are not greater, considering probability and magnitude, than those ordinarily encountered in daily life or during the performance of routine closed-house conditions.

Benefits

This research will provide data to improve indoor air quality inexpensively and energy-efficiently at test sites exhibiting elevated radon levels. Results will compare background and mitigated radon concentrations and energy usage under various conditions to quantify air improvement and energy efficiency and determine optimal operational modes for the system to most effectively reduce radon levels and other indoor air pollutants as well as to provide the highest net energy gain.

Since all commercially available ventilation/pressurization radon mitigation systems operate with a net energy loss due to the introduction of below ambient-temperature air indoors, this project will document the effectiveness of a unique, environmentally-appropriate approach to improving indoor air quality while conserving energy.

Other Procedures

Once elevated radon levels have been determined, volunteers are advised to seek professional mitigation advice if desired. In most cases, radon reduction efforts will be performed as quickly and effectively, at no cost to homeowners, through participation in this project as achievable through professional contractors.

Confidentiality

Test site locations and owners will remain confidential and identified only by street names in all written reports to safeguard the privacy of participants. Close-up photographs of the installed Solar Radon Reduction Systems and test conditions may be requested by the researcher.

Participation

Participation in this project is strictly voluntary. Cooperation with maintaining closed-house conditions when necessary will be appreciated. Participants will be given the option of keeping the installed solar panel at the completion of the project. Participants may discontinue participation at any time and refusal to participate will involve no penalty or loss of benefits to which they are entitled.

The researcher may request entrance and demonstration of the installed SRRS to university and governmental officials with at least 24 hours notification. Participants will also be asked to provide or allow access to past utility records for the site.

Participants may contact the office of the Human Subjects Coordinator, University of Northern Iowa, (319) 273-2748, for answers to questions about the research and about the rights of research subjects.

INFORMED CONSENT

I am fully aware of the nature and extent of my participation in this project as stated above and the possible risks arising from it. I hereby agree to participate in this project. I acknowledge that I have received a copy of this consent statement.

____

(Signature of subject or responsible agent) Date

____

(Printed name of subject)

____

(Signature of investigator) Date

APPENDIX D: EQUIPMENT SPECIFICATIONS

Solar Panel Temperature-Trigger

National Semiconductor Precision Centigrade Temperature Sensors (LM35) were incorporated into the SRRS design to detect solar panel air temperature for the fan control units. The integrated-circuit sensor produces voltage signal values linearly proportional to its Celsius temperature; a temperature of 20°C inside the collector registers as 0.20 V. Its thermal time constant is reported to be 35 seconds in still air, with 100% thermal response at 3 minutes; its accuracy is 0.25°C at room temperature and 0.75°C over a range of -55 to +150°C. As it draws only 60 µA from its supply, it has low self-heating of 0.08°C in still air. The sensors used for this study were hermetically sealed in aluminum casing by the College of Natural Sciences Electronics Shop and installed inside the solar panels and wired into SRRS control units at the test sites.

PC Datalogging Connections

Fan operation was logged by PCs at each site, which used parallel port pin 13 to detect 5 V on/off signals sent through the electronic control unit data line.

Null modem cables connect the MTL Radon Alarms to PCs with 9-pin female DB connections to the radon monitor and 25-pin female serial port connectors with three sets of pins reversed: 2 (transmit data) and 3 (receive data); 4 (request to send) and 6 (data set ready); and 5 (clear to send) and 20 (data terminal ready). The manufacturer reports the device's 9-pin serial connector functions for pin 2 (serial data input), 3 (serial data output), 5 (signal ground), and 6 (data set ready input), although additional pins are used by MTL Mitigation Controllers.

Pressure Differential

Basement/outdoor pressure differential data was obtained with Omega Differential Pressure Transducers (PX-163-2.5 BD5V), rated to measure small pressure differences of ±2.5 inches of H_2O. The signal-conditioned pressure sensors are temperature-compensated solid-state piezoresistive devices and are rated for low hysteresis and long-term stability. The sensor measured the difference between pressures on two sides of the transducer; one was exposed to the outdoors with flexible tubing, and the other was open to basement pressure. The units were calibrated with a water column and syringe to apply a known pressure in cm H_2O and powered with 5 V supply. Based on manufacturer's output data, the calculated value at zero pressure was 2.1875 V, and the conversion factor was determined with the formula:

$$\text{Conversion Factor in cm/mV} = \text{Max Pressure} / (V_{max} - V_0),$$

where Maximum Pressure = 6.35 cm H_2O,

V_{max} = output at 6.35 cm H_2O in mV = 3750 mV, and

V_0 = output at 0 cm H_2O in mV = 2187.5 mV.

Thus the resulting calculated multiplier was 0.004064 cm/mV. However, the two gauges showed slightly different V_0 values of 2136 mV (unit A) and 2220 mV (unit B), which corresponded to multiplier and offset values shown in Table 6. Pressure units were later converted from cm H_2O to Pa.

Solar Radiation

Designed specifically for energy assessment and solar collector evaluation, Li-Cor Pyranometer light sensors (LI-200SA) were used to measure 400-1100 nm solar radiation in Watts per square meters (W/m^2); a Millivolt Adapter (2200S) with 147 Ohm resistance is required for use with the datalogger. Conversion factors shown in Table 6 were recalculated from the multipliers provided by the manufacturer for each sensor with the formula:

Conversion Factor = -1000 (Multiplier / Resistance),
where Multiplier = $-12.39\ Wm_{-2}/\mu A$ (sensor A) or
$-10\ Wm_{-2}/\mu A$ (sensor B), and
Resistance = 147 Ohms = 147 $\mu V/\mu A$.

The sensors were affixed flush to the collector face (vertical to ground surface) at the center of the collectors.

Temperatures and Humidity Monitored

Temperature and duplicate sensors used in this study were found to agree within 1-2%.

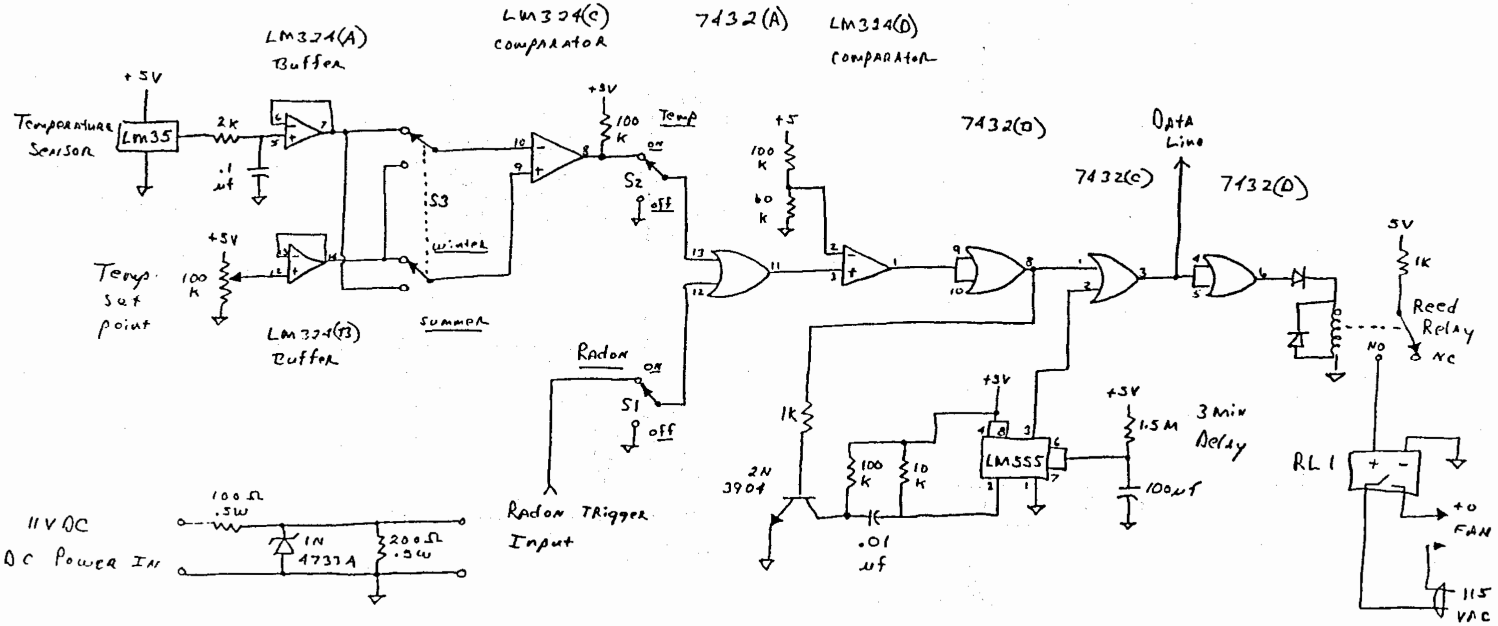
Fine-wire constantan/copper thermocouples were used to measure inlet, outlet, and furnace duct temperatures at Sager and Lovejoy, and the 21X internal thermistor served as a reference for the thermocouples and recorded average basement temperatures. During closed house testing, outlet temperature sensors measured indoor basement temperatures to establish average indoor temperatures. Campbell reports the internal thermistor's accuracy is typically better than ±2°C in the range of -35 to +50°C. Copper/constantan thermocouple types have been rated by the American National Standards Institute as having error limits of ±1.0°C or 0.75%, but Campbell reports that measurements in the environmental range are typically more accurate.

Omega RD-Temp Loggers were used to measure outlet temperatures at Byron, Vermont, and Washington. These relatively inexpensive stand-alone units ($99 each) can store up to 1800 measurements in EEPROM with the duration adjustable to 31 settings between 15 minutes and 360 days with corresponding intervals of 0.5 seconds to 4.8 hours. The setting of 12 minute intervals lasting for 15 days was selected for this study. The RD-Temp sensor, a 10K (44006 type) thermistor, and a 2-year lithium cell battery are encased in a matchbook-sized plastic box (32 x 44.5 x 14.7 mm); the logger is launched, downloaded, and its data plotted by PC software. The encased unit's measurement range is -39 to 75°C; its resolution is 0.35°C at 25°C but degrades at extreme temperatures. Between 0 and 80°C, the thermistor is accurate within ±0.2°C; below 0°C the error can increase to as much as ±0.4 by -40°C, and above 80°C it increases to about ±0.6°C by 120°C. The RD-Temp's reported thermal time constant is about 5 minutes in water and longer in air.

Vaisala "Humitter" integrated relative humidity transmitters were used to measure relative humidity at Sager and Lovejoy. These inexpensive sensors ($150 each) use an Intercap interchangeable capacitive humidity sensor which operates on the principle of a change in electrical property proportional to moisture content and temperature. A thin-film polymer that responds quickly to humidity is sandwiched between two gold plates, forming a capacity sensitive to humidity. Its accuracy is reported to be better than ±3% RH for the measuring range of 10 to 90% RH and has a stability of ±2% RH over 2 years. The temperature dependance is <±2% from -10 to +60°C.

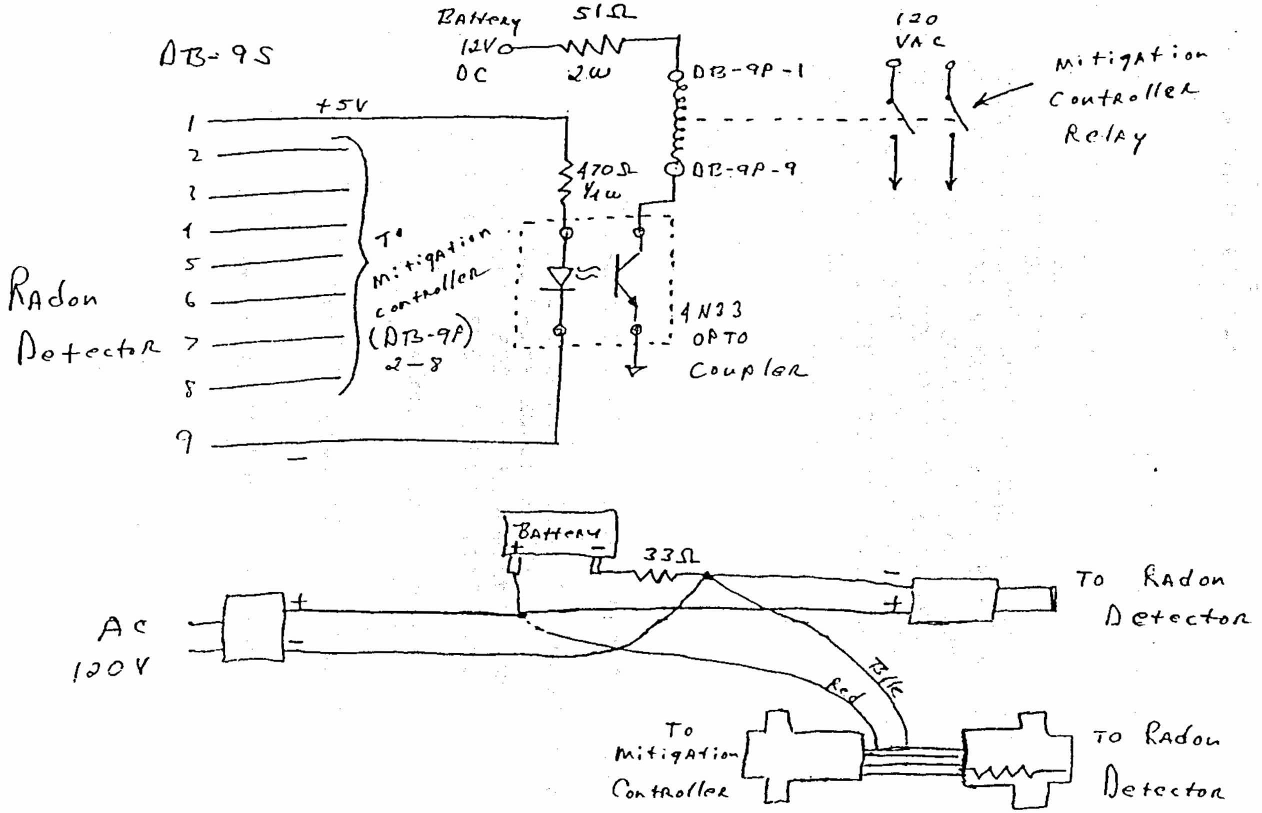
As a supplement to digital data acquisition, Dickson Temperature/Humidity Trace Recorders (THP7FM2) were used to document first floor environmental conditions at Lovejoy and Sager. These battery-operated devices use bimetallic strips to measure temperature and hair hygrometers to determine relative humidity (RH) and continuously record readings on circular 7-day charts. The model used in this study operates in the range of 0-100°F and are not recommended for environments below 15% or exceeding 85% RH.

SOLAR RADON REDUCTION SYSTEM ENVIRONMENTAL MONITOR CONTROLLER
PATENT PENDING



designed by Bruce G. Early, College of Natural Sciences Electronics Shop, and Peter L. Hoekje, Physics Department, University of Northern Iowa

MTL RADON ALARM AND MITIGATION CONTROLLER
DC POWER SUPPLY/BATTERY BACKUP CONNECTOR CABLE



designed by Bruce G. Early, College of Natural Sciences
Electronics Shop, and Peter L. Hoekje, Physics Department,
University of Northern Iowa

APPENDIX F: DATA ACQUISITION PROGRAMS

SETUP.BAS

```
5    OPEN "DL.CFG" FOR OUTPUT AS #1
10   INPUT "RADON FILENAME (eg SAG1015.RAD)"; RF$
15   OPEN RF$ FOR OUTPUT AS #2
16   INPUT "FAN STATUS FILENAME (eg SAG1015.FAN)"; FF$
17   OPEN FF$ FOR OUTPUT AS #3
18   INPUT "FAN STATUS (0 = off, 1 = on)"; FS$
20   INPUT "TEST HOUSE"; TH$
22   INPUT "RADON ALARM #"; RA$
24   INPUT "DATE (MM-DD-YYYY)"; DA$
25   DATE$ = DA$
30   INPUT "TEST MODE (WT=winter temp; RT=radon trigger; WR=both)";
     TM$
32   INPUT "SET POINT TEMP (C)"; ST$
34   INPUT "GAS METER"; GM$
35   INPUT "ELECTRIC METER"; EM$
36   INPUT "UPSTAIRS CURRENT; AVERAGE RADON (PRINT OUT)"; UR$
37   INPUT "FAN OUTLET TEMP & HUMIDITY (C; %)"; FO$
38   INPUT "BASEMENT TEMP & HUMIDITY (C; %)"; BM$
39   INPUT "OUTDOOR TEMP & HUMIDITY (C; %)"; OD$
40   INPUT "FURNACE VENT TEMP & HUMIDITY (C; %)"; FV$
41   INPUT "UPSTAIRS TEMP & HUMIDITY (C; %)"; UP$
48   INPUT "COMMENTS"; CM$
50   INPUT "TIME (HH:MM:SS)"; TI$
51   TIME$ = TI$

60   PRINT #1, RF$
61   PRINT #1, FF$
62   PRINT #1, FS$

70   PRINT #2, TH$; ", Radon #"; RA$; ", Started "; DA$; TI$; ", Fan
     Status "; FS$
71   PRINT #2, TM$; "Mode, Set Point"; ST$; ",  Gas"; GM$; ",
     Electric"; EM$; ", Upstairs Radon"; UR$
72   PRINT #2, "Fan Outlet"; FO$; ", Basement"; BM$; ", Outdoors";
     OD$; ", Furnace Vent"; FV$; ", Upstairs"; UP$
73   PRINT #2, CM$
80   PRINT #2, "Radon Level, Radon Clock, Computer Time, Computer
     Date, Fan Status (0=off)"

85   PRINT #3, TH$; ", Started "; DA$; TI$; ", Fan Status "; FS$; ",
     "; TM$; "Mode, "
86   PRINT #3, CM$
87   PRINT #3, "Fan Status, Elapsed Fan Time, Fan Hours Today, Time,
     Date, Radon"

90   CLOSE #1
100  CLOSE #2
101  CLOSE #3
110  END
```

DL.BAS

```
10  OPEN "DL.CFG" FOR INPUT AS #1        'Created with Setup.EXE
20  LINE INPUT #1, RF$  'Radon filename
21  LINE INPUT #1, FF$  'Fan filename
27  LINE INPUT #1, FS$  'Fan Status
33  CLOSE #1
34  LASTFAN% = VAL(FS$)                  'Sets LASTFAN
35  FAN% = VAL(FS$)                      'Sets FAN
36  LASTTIME = TIMER                     'Sets fan timer first time

40  THOUR = TIMER                        'Sets up hourly wait loop
80  TIME = TIMER                         'Time Mark: Note Timer
    always changing, 0 at midnight
85  IF DATE$ = "01-01-1980" THEN GOTO 1100    'Power Outage Loop

90  OPEN "COM1:1200,N,8,1,RB1000,cs0,ds0,CD0" FOR RANDOM AS #1 LEN =
    1000
100 OPEN RF$ FOR APPEND AS #2 LEN = 10000     'Opens *.RAD file for
    storage
110 PRINT #1, "P";                       'Sends Download command

130 IF LOC(1) > 48 THEN GOTO 140       'Starts Download
132 IF TIMER-TIME > 20 THEN GOTO 1000 ELSE GOTO 130 'Timeout Loop
140 LINE INPUT #1, M$                    'Download line by line
150 N$ = MID$(M$, 2, 7)                  'Extract first word of line
160 IF N$ = "Elapsed" THEN RADONCLOCK$ = MID$(M$, 23, 18)
170 IF N$ = "Current" THEN RADON$ = MID$(M$, 21, 4): GOTO 210
200 GOTO 130                             'Try Download Again
210 PRINT "Radon Level is "; RADON$
211 PRINT "Radon Clock is "; RADONCLOCK$
212 PRINT "Computer Time is "; TIME$
220 PRINT #2, RADON$; ", "; RADONCLOCK$; ", "; TIME$; ", "; DATE$;
    ", "; FAN%
    TIME = TIMER
    REM There are 187 characters leftover after the d/l

230 lastsize = LOC(1)
    TIME = TIMER                         'Time Mark
232 IF LOC(1)>lastsize THEN GOTO 230     'Radon still sending
    IF TIMER-TIME < 2 THEN GOTO 232      'Wait 2 sec after last send

240 CLOSE #1                             'End communications.
250 CLOSE #2

260 OPEN "LASTTIME.CFG" FOR OUTPUT AS #4      'Power Outage Loop
262 PRINT #4, RADONCLOCK$
264 PRINT #4, TIME$
265 PRINT #4, DATE$
266 CLOSE #4

309 REM RADON & FAN WAIT LOOPS, MIDNIGHT RESETTING
310 NEWTIME = TIMER                           'New time Mark
311 MINUTES$ = MID$(TIME$, 4, 2)                     'Defines Minutes
312  IF MINUTES$ = "00" AND TIMER - THOUR >= 60 THEN GOTO 40 'Hourly
    wait loop
313  HOURS$ = MID$(TIME$, 1, 2)                      'Defines Hours
314  IF HOURS$ = "00" THEN LASTFANHOURS = 0          'Resets Fan Hours
     at midnight
```

```
315   IF NEWTIME < LASTTIME THEN LASTTIME = 0         'Resets Fan Loop
      wait at midnight
316   IF NEWTIME < THOUR THEN THOUR = NEWTIME         'Resets THOUR
      after midnight
317   IF NEWTIME - LASTTIME > 20 THEN GOTO 1200       'Checks fan every
      20 sec
318   GOTO 310                                        'Loop
319   REM GOTO 1200                                   'TEMP FIX
400   STOP

1000 REM Timeout loop
      PRINT "Monitor not responding -- check connections!"
      CLOSE #1
      CLOSE #2
      GOTO 1200

1100 REM Power outage loop
     REM Open RF$ and get last radonclock$, time$
1105 OPEN "LASTTIME.CFG" FOR INPUT AS #5
1110 LINE INPUT #5, LASTRTIME$
1111 LINE INPUT #5, LASTCTIME$
1112 LINE INPUT #5, LASTDATE$
1119 CLOSE #5
1120 LASTRHOUR$ = MID$(LASTRTIME$, 1, 6)
1121 LASTRMIN$ = MID$(LASTRTIME$, 8, 5)
1122 LASTRSEC$ = MID$(LASTRTIME$, 15, 5)
1123 LASTCHOUR$ = MID$(LASTCTIME$, 1, 2)
1124 LASTCMIN$ = MID$(LASTCTIME$, 4, 2)
1125 LASTCSEC$ = MID$(LASTCTIME$, 7, 5)
1126 LASTRHMS% = (VAL(LASTRHOUR$) * 3600) + (VAL(LASTRMIN$) * 60) +
     VAL(LASTRSEC$)
1127 LASTCHMS% = (VAL(LASTCHOUR$) * 3600) + (VAL(LASTCMIN$) * 60) +
     VAL(LASTCSEC$)

     REM download new radon report, line by line, including all 10
     stored radon readings
1131 OPEN "COM1:1200,N,8,1,RB1000,cs0,ds0,CD0" FOR RANDOM AS #6 LEN
     = 1000
1132 OPEN RF$ FOR APPEND AS #7 LEN = 10000
1133 PRINT #6, "P";                             'Sends Download command
1134 IF LOC(6) > 48 THEN GOTO 1140                  'Starts Download
1136 IF TIMER-TIME>20 THEN GOTO 1000 ELSE GOTO 1134 'Timeout Loop
1140 LINE INPUT #6, M$                           'Download line by line
1141 N$ = MID$(M$, 2, 7)                         'Extract first word of line
1143 IF N$ = "Elapsed" THEN RADONCLOCK$ = MID$(M$, 23, 18)
1144 IF N$ = "Current" THEN RADON$ = MID$(M$, 21, 4): GOTO 1150
1148 GOTO 1134                                  'Try Download Again
1150 TIME = TIMER
1151 lastsize = LOC(6)
     TIME = TIMER
1153 IF LOC(6) > lastsize THEN GOTO 1151
     IF TIMER - TIME < 2 THEN GOTO 1153
1160 PRINT M$
1161 PRINT "Radon Level is "; RADON$
1162 PRINT "Radon Clock is "; RADONCLOCK$
1164 PRINT #7, M$                       'Writes entire report to file
1165 PRINT #7, RADON$; ", "; RADONCLOCK$; ", "; FAN%
1166 CLOSE #6                           ' End communications.
1167 CLOSE #7
```

```
1170 REM  RESET COMP CLOCK BASED ON RADONCLOCK
1175 RHOUR$ = MID$(RADONCLOCK$, 1, 6)
1176 RMIN$ = MID$(RADONCLOCK$, 8, 5)
1177 RSEC$ = MID$(RADONCLOCK$, 15, 5)
1178 RHMS% = (VAL(RHOUR$) * 3600) + (VAL(RMIN$) * 60) + VAL(RSEC$)
     REM subtract new radonclock$ from old
1180 TIMEMISSED% = RHMS% - LSTRHMS%
     REM add this to old time$
1182 CHMS = TIMEMISSED% + LASTCHMS%
     REM CONVERT TIMES BACK TO HR:MIN:SEC
1184 HR% = INT(CHMS / 3600)
1186 MN% = INT(((CHMS / 3600) - HR%) * 60)
1188 SEC = (((((CHMS / 3600) - HR%) * 60) - MN%) * 60)
1189 HR$ = STR$(HR%)
1190 MN$ = STR$(MN%)
1191 SEC$ = STR$(SEC)
1192 IF SEC = 60 THEN SEC$ = "00"
1193 IF SEC = 60 THEN MN$ = STR$(MN% + 1)
     REM RESET COMPUTER TIME!
1195 TIME$ = LTRIM$(HR$) + ":" + LTRIM$(MN$) + ":" + LTRIM$(SEC$)
1196 DATE$ = LASTDATE$
1198 TIME = TIMER
1199 GOTO 310

1200 REM Fan status loop
1220 FAN% = (INP(3 * 256 + 7 * 16 + 9) AND 16) / 16
1230 IF FAN% = LASTFAN% THEN GOTO 310          'Check if changed
1232 FANTIME = TIMER - LASTTIME
1233 IF FAN% = 0 THEN
     FANOFF = TIMER
     FANONTIME = FANOFF - FANON
     FANHOURS = FANONTIME + LASTFANHOURS
     ELSE FANON = TIMER
     END IF
1240 PRINT "Fan status is (0=off) "; FAN%
1246 PRINT "Elapsed Fan Time is "; FANTIME
1247 PRINT "Fan Hours Today is "; FANHOURS
1249 PRINT "Computer Time is "; TIME$
1260 OPEN FF$ FOR APPEND AS #3 LEN = 10000
1270 PRINT #3, FAN%; ", "; FANTIME; ", "; FANHOURS; ", "; TIME$; ",
     "; DATE$; ", "; RADON$
1280 CLOSE #3
1300 LASTFAN% = FAN%          'Sets for next check
1310 LASTTIME = TIMER         'Resets fanloop Mark
1320 LASTFANHOURS = FANHOURS  'Sets for next add-on

1400 GOTO 310
9999 END
```

LOGOUT.BAS

```
5   OPEN "DL.CFG" FOR INPUT AS #1
10  LINE INPUT #1, RF$
12  LINE INPUT #1, FF$
13  CLOSE #1
15  OPEN RF$ FOR APPEND AS #2
17  OPEN FF$ FOR APPEND AS #3
18  INPUT "FAN STATUS (0 = off, 1 = on)"; FS$
24  INPUT "DATE (MM-DD-YYYY)"; DA$
30  INPUT "TEST MODE (WT=winter temp; RT=radon trigger; WR=both)";
    TM$
32  INPUT "SET POINT TEMP (C)"; ST$
34  INPUT "GAS METER"; GM$
35  INPUT "ELECTRIC METER"; EM$
36  INPUT "UPSTAIRS CURRENT; AVERAGE RADON (PRINT OUT)"; UR$
37  INPUT "FAN OUTLET TEMP & HUMIDITY (C; %)"; FO$
38  INPUT "BASEMENT TEMP & HUMIDITY (C; %)"; BM$
39  INPUT "OUTDOOR TEMP & HUMIDITY (C; %)"; OD$
40  INPUT "FURNACE VENT TEMP & HUMIDITY (C; %)"; FV$
41  INPUT "UPSTAIRS TEMP & HUMIDITY (C; %)"; UP$
48  INPUT "COMMENTS"; CM$
50  INPUT "TIME (HH:MM:SS)"; TI$
51  TIME$ = TI$

70  PRINT #2, "Ended "; DA$; TI$; ", Fan Status "; FS$
71  PRINT #2, TM$; "Mode, Set Point"; ST$; ", Gas"; GM$; ",
    Electric"; EM$; ", Upstairs Radon"; UR$
72  PRINT #2, "Fan Outlet"; FO$; ", Basement"; BM$; ", Outdoors";
    OD$; ", Furnace Vent"; FV$; ", Upstairs"; UP$
73  PRINT #2, CM$; CHR$(12)

85  PRINT #3, "Ended "; DA$; TI$; ", Fan Status "; FS$; ", "; TM$;
    "Mode, "
86  PRINT #3, CM$; CHR$(12)

100 CLOSE #2
101 CLOSE #3
110 END
```

SRRS 21X Micrologger Program

Mode	Program #	Instruction	Parameters	Description
*5A			94A	Set year
			(335)A	Set day of year (335 = Dec 1)
			(1425)A	Set time in HHMM (1425 = 2:25 pm)
*1A			60A	Program in table 1; 1 min measurement interval
	01: Pressure Differential	P04		Excite, Delay, Single Ended (SE) Signal
			01:1	1 Sensor
			02:5	5000 mV Range
			03:1	SE Channel 1
			04:1	Excite Channel 1
			05:100	Delay 1 sec
			06:5000	Excite with 5 V
			07:1	Store in location 1
			08:(D00393)	Multiplier (0.00393 for A, 0.00413 for B)
			09:(8D395C)	Offset (-8.395 for A, -9.169 for B)
	02: Solar Radiation	P02		Differential (Diff) Signal
			01:1	1 Sensor
			02:2	15 mV Range (1000 W/m² / 85 = 13 mV max)
			03:3	Diff Channel 2
			04:2	Store in location 2
			05:(84D289)	Multiplier (84.289 for -12M, 71.429 for -10M)
			06:0	Offset = 0
	03: 21X Temp	P17	01:3	Store in location 3
	04: Thermocouples	P14		Thermocouple (TC) Temp Diff
			01:3	3 Sensors
			02:1	5 mV Range
			03:3	Diff Channels 3, 4, 5, and 6
			04:1	TC Type Copper/Constantan
			05:3	Panel ref in location 3
			06:4	Store TC in locations 4, 5, and 6
			07:1	Multipler = 1
			08:0	Offset = 0
	05: RH%	P01		SE voltage Signal
			01:2	2 Sensors
			02:5	5000 mV Range
			03:15	SE channels 15 and 16
			04:7	Store in location 7 and 8
			05:D1	Multiplier = 0.1
			06:0	0 Offset
	06: Battery Voltage	P10	01:9	Store Battery V in location 9
	07: Processing	P92	01:0	Process at 0 min into interval
			02:12	12 min intervals
			03:10	Set output flag high
	08: Store Time	P77	01:0110	Store day, hours, and min
	09: Average Data	P71	01:9	Data in 9 input locations
			02:01	Start averaging at input location 1
*A 28				Repartion memory (clear final storage)
*0				Start logging

Datalogging Input Table

Location	Parameter	Instruction	Units	Sensor
1	Pressure	P04	cm H2O	Omega Pressure Transducer
2	Solar Radiation	P02	W/m²	LiCor Pyranometer Sensor
3	Basement Temp	P17	°C	21X Internal Thermistor
4	Fan Outlet Temp	P14	°C	Thermocouple 1
5	Outdoor/Inlet Temp	P14	°C	Thermocouple 2
6	Furnace Duct Temp	P14	°C	Thermocouple 3
7	Fan Outlet Humidity	P01	%RH	Vaisala Humitter 1
8	Furnace Duct Humidity	P01	%RH	Vaisala Humitter 2
9	Power Supply	P10	mV	AC/DC Transformer or 12V Battery

APPENDIX G: ANOVA RESULTS

```
Tuesday, April 11, 1995, 14:36:10

One Way Analysis of Variance

Normality Test:         Failed         (P = 0.0022)


Test execution ended by user request, ANOVA on Ranks begun

Tuesday, April 11, 1995, 14:36:10

Kruskal-Wallis One Way Analysis of Variance on Ranks

Group                   N             Missing
Control1                253           13
Control 2               253            5
Control 3               253           13
Control 4               253           13
Control 5               253           13

Group                   Median        25%            75%
Control1                 4.00          3.65           4.40
Control 2                4.50          4.20           5.10
Control 3                4.70          4.20           5.70
Control 4                5.30          4.80           5.90
Control 5                6.00          5.50           6.40

H =  507.0 with 4 degrees of freedom.  (P = <0.0001)

The differences in the median values among the treatment groups are greater
than would be expected by chance; there is a statistically significant
difference  (P = 2.09E-108)

To isolate the group or groups that differ from the others use a multiple
comparison procedure.

All Pairwise Multiple Comparison Procedures (Dunn's Method) :

Comparison              Diff of Ranks p              Q
Control 5 vs Control1    677.8         5              21.30
Control 5 vs Control 2   469.1         4              14.86
Control 5 vs Control 3   375.2         3              11.79
Control 5 vs Control 4   242.2         2               7.61
Control 4 vs Control1    435.6         4              13.69
Control 4 vs Control 2   226.8         3               7.19
Control 4 vs Control 3   132.9         2               4.18
Control 3 vs Control1    302.7         3               9.51
Control 3 vs Control 2    93.9         2               2.97
Control 2 vs Control1    208.8         2               6.61

Comparison              P<0.05
Control 5 vs Control1   Yes
Control 5 vs Control 2  Yes
Control 5 vs Control 3  Yes
Control 5 vs Control 4  Yes
Control 4 vs Control1   Yes
Control 4 vs Control 2  Yes
Control 4 vs Control 3  Yes
Control 3 vs Control1   Yes
Control 3 vs Control 2  Yes
Control 2 vs Control1   Yes
```

```
Tuesday, April 11, 1995, 14:37:14

One Way Analysis of Variance

Normality Test:         Failed        (P = <0.0001)


Test execution ended by user request, ANOVA on Ranks begun

Tuesday, April 11, 1995, 14:37:14

Kruskal-Wallis One Way Analysis of Variance on Ranks

Group                   N              Missing
Byron 1                 253            13
Byron 2                 253             9
Byron 3                 253             9
Byron 4                 253            64
Byron 5                 253            35

Group                   Median         25%            75%
Byron 1                  9.10           7.40           10.9
Byron 2                 11.00           8.80           14.3
Byron 3                 12.85          10.10           16.9
Byron 4                 11.80          10.30           13.8
Byron 5                 12.30          10.40           23.2

H =  191.1 with 4 degrees of freedom.  (P = <0.0001)

The differences in the median values among the treatment groups are greater
than would be expected by chance; there is a statistically significant
difference  (P = 3.10E-040)

To isolate the group or groups that differ from the others use a multiple
comparison procedure.

All Pairwise Multiple Comparison Procedures (Dunn's Method) :

Comparison              Diff of Ranks  p              Q
Byron 5 vs Byron 1       358.37         5              11.6859
Byron 5 vs Byron 2       155.12         4               5.0781
Byron 5 vs Byron 4       101.90         3               3.1281
Byron 5 vs Byron 3         1.34         2               0.0437
Byron 3 vs Byron 1       357.04         4              11.9817
Byron 3 vs Byron 2       153.78         3               5.1823
Byron 3 vs Byron 4       100.57         2               3.1664
Byron 4 vs Byron 1       256.47         3               8.0458
Byron 4 vs Byron 2        53.22         2               1.6755
Byron 2 vs Byron 1       203.25         2               6.8209

Comparison              P<0.05
Byron 5 vs Byron 1      Yes
Byron 5 vs Byron 2      Yes
Byron 5 vs Byron 4      Yes
Byron 5 vs Byron 3      No
Byron 3 vs Byron 1      Yes
Byron 3 vs Byron 2      Yes
Byron 3 vs Byron 4      Yes
Byron 4 vs Byron 1      Yes
Byron 4 vs Byron 2      No
Byron 2 vs Byron 1      Yes
```

```
Wednesday, April 12, 1995, 11:31:03

One Way Analysis of Variance

Normality Test:          Failed        (P = 0.0002)


Test execution ended by user request, ANOVA on Ranks begun

Wednesday, April 12, 1995, 11:31:03

Kruskal-Wallis One Way Analysis of Variance on Ranks

Group                    N             Missing
Lovejoy 1                253           13
Lovejoy 2                253            6
Lovejoy 3                253           10
Lovejoy 4                253           13
Lovejoy 5                253           13

Group                    Median        25%            75%
Lovejoy 1                  5.10          3.50           7.95
Lovejoy 2                 20.70         17.60          24.50
Lovejoy 3                  5.10          4.02           6.37
Lovejoy 4                 14.80         11.55          17.30
Lovejoy 5                  6.80          5.70           8.10

H =  917.2 with 4 degrees of freedom.  (P = <0.0001)

The differences in the median values among the treatment groups are greater
than would be expected by chance; there is a statistically significant
difference  (P = 3.20E-197)

To isolate the group or groups that differ from the others use a multiple
comparison procedure.

All Pairwise Multiple Comparison Procedures (Dunn's Method) :

Comparison               Diff of Ranks p              Q
Lovejoy 2 vs Lovejoy 3    757.8        5               24.00
Lovejoy 2 vs Lovejoy 1    719.8        4               22.73
Lovejoy 2 vs Lovejoy 5    588.2        3               18.57
Lovejoy 2 vs Lovejoy 4    184.7        2                5.83
Lovejoy 4 vs Lovejoy 3    573.1        4               18.02
Lovejoy 4 vs Lovejoy 1    535.1        3               16.78
Lovejoy 4 vs Lovejoy 5    403.6        2               12.65
Lovejoy 5 vs Lovejoy 3    169.6        3                5.33
Lovejoy 5 vs Lovejoy 1    131.6        2                4.12
Lovejoy 1 vs Lovejoy 3     38.0        2                1.19

Comparison               P<0.05
Lovejoy 2 vs Lovejoy 3   Yes
Lovejoy 2 vs Lovejoy 1   Yes
Lovejoy 2 vs Lovejoy 5   Yes
Lovejoy 2 vs Lovejoy 4   Yes
Lovejoy 4 vs Lovejoy 3   Yes
Lovejoy 4 vs Lovejoy 1   Yes
Lovejoy 4 vs Lovejoy 5   Yes
Lovejoy 5 vs Lovejoy 3   Yes
Lovejoy 5 vs Lovejoy 1   Yes
Lovejoy 1 vs Lovejoy 3   No
```

```
Tuesday, April 11, 1995, 14:39:23

One Way Analysis of Variance

Normality Test:         Failed        (P = <0.0001)


Test execution ended by user request, ANOVA on Ranks begun

Tuesday, April 11, 1995, 14:39:23

Kruskal-Wallis One Way Analysis of Variance on Ranks

Group                   N              Missing
Sager 1                 253            112
Sager 2                 253             7
Sager 3                 253            162
Sager 4                 253            13
Sager 5                 253            13

Group                   Median         25%            75%
Sager 1                  15.40          14.30          16.10
Sager 2                   6.10           5.30           7.20
Sager 3                  11.40          10.20          11.80
Sager 4                   7.50           6.20           9.15
Sager 5                  12.35          11.60          13.30

H =  773.9 with 4 degrees of freedom.  (P = <0.0001)

The differences in the median values among the treatment groups are greater
than would be expected by chance; there is a statistically significant
difference  (P = 3.46E-166)

To isolate the group or groups that differ from the others use a multiple
comparison procedure.

All Pairwise Multiple Comparison Procedures (Dunn's Method) :

Comparison              Diff of Ranks  p              Q
Sager 1 vs Sager 2       680.6          5              23.29
Sager 1 vs Sager 4       569.3          4              19.39
Sager 1 vs Sager 3       322.8          3               8.68
Sager 1 vs Sager 5       196.9          2               6.71
Sager 5 vs Sager 2       483.7          4              19.27
Sager 5 vs Sager 4       372.4          3              14.75
Sager 5 vs Sager 3       125.9          2               3.70
Sager 3 vs Sager 2       357.8          3              10.54
Sager 3 vs Sager 4       246.5          2               7.24
Sager 4 vs Sager 2       111.3          2               4.43

Comparison     ,        P<0.05
Sager 1 vs Sager 2      Yes
Sager 1 vs Sager 4      Yes
Sager 1 vs Sager 3      Yes
Sager 1 vs Sager 5      Yes
Sager 5 vs Sager 2      Yes
Sager 5 vs Sager 4      Yes
Sager 5 vs Sager 3      Yes
Sager 3 vs Sager 2      Yes
Sager 3 vs Sager 4      Yes
Sager 4 vs Sager 2      Yes
```

```
Tuesday, April 11, 1995, 14:40:09

One Way Analysis of Variance

Normality Test:          Failed          (P = 0.0011)


Test execution ended by user request, ANOVA on Ranks begun

Tuesday, April 11, 1995, 14:40:09

Kruskal-Wallis One Way Analysis of Variance on Ranks

Group                   N              Missing
Vermont 1               253             7
Vermont 2               253            103
Vermont 3               253            13
Vermont 4               253            13
Vermont 5               253            13

Group                   Median         25%            75%
Vermont 1                10.00           8.60           11.2
Vermont 2                18.50          17.30           20.0
Vermont 3                11.00           9.60           11.7
Vermont 4                17.70          14.00           20.6
Vermont 5                11.10           9.30           12.8

H =  661.6 with 4 degrees of freedom.  (P = <0.0001)

The differences in the median values among the treatment groups are greater
than would be expected by chance; there is a statistically significant
difference  (P = 7.20E-142)

To isolate the group or groups that differ from the others use a multiple
comparison procedure.

All Pairwise Multiple Comparison Procedures (Dunn's Method) :

Comparison              Diff of Ranks  p              Q
Vermont 2 vs Vermont 1   644.7          5              19.31
Vermont 2 vs Vermont 3   542.6          4              16.18
Vermont 2 vs Vermont 5   512.9          3              15.29
Vermont 2 vs Vermont 4    96.1          2               2.87
Vermont 4 vs Vermont 1   548.6          4              18.76
Vermont 4 vs Vermont 3   446.5          3              15.18
Vermont 4 vs Vermont 5   416.8          2              14.17
Vermont 5 vs Vermont 1   131.8          3               4.51
Vermont 5 vs Vermont 3    29.7          2               1.01
Vermont 3 vs Vermont 1   102.0          2               3.49

Comparison              P<0.05
Vermont 2 vs Vermont 1  Yes
Vermont 2 vs Vermont 3  Yes
Vermont 2 vs Vermont 5  Yes
Vermont 2 vs Vermont 4  Yes
Vermont 4 vs Vermont 1  Yes
Vermont 4 vs Vermont 3  Yes
Vermont 4 vs Vermont 5  Yes
Vermont 5 vs Vermont 1  Yes
Vermont 5 vs Vermont 3  No
Vermont 3 vs Vermont 1  Yes
```

```
Tuesday, April 11, 1995, 14:40:46

One Way Analysis of Variance

Normality Test:         Failed        (P = <0.0001)


Test execution ended by user request, ANOVA on Ranks begun

Tuesday, April 11, 1995, 14:40:46

Kruskal-Wallis One Way Analysis of Variance on Ranks

Group                   N             Missing
Wash 1                  253            8
Wash 2                  253           11
Wash 3                  253            4
Wash 4                  253           13
Wash 5                  253           13

Group                   Median        25%           75%
Wash 1                   2.80          2.70          3.00
Wash 2                   2.80          2.70          3.00
Wash 3                   2.80          2.50          3.00
Wash 4                   2.80          2.70          3.00
Wash 5                   2.90          2.65          3.20

H =  28.3 with 4 degrees of freedom.  (P = <0.0001)

The differences in the median values among the treatment groups are greater
than would be expected by chance; there is a statistically significant
difference  (P =  0.0000106)

To isolate the group or groups that differ from the others use a multiple
comparison procedure.

All Pairwise Multiple Comparison Procedures (Dunn's Method) :

Comparison              Diff of Ranks p             Q
Wash 5 vs Wash 3         157.06        5             4.9864
Wash 5 vs Wash 1          58.48        4             1.8492
Wash 5 vs Wash 4          56.10        3             1.7650
Wash 5 vs Wash 2          29.59        2             0.9329
Wash 2 vs Wash 3         127.47        4             4.0554
Wash 2 vs Wash 1          28.89        3             0.9154
Wash 2 vs Wash 4          26.51        2             0.8358
Wash 4 vs Wash 3         100.95        3             3.2052
Wash 4 vs Wash 1           2.38        2             0.0751
Wash 1 vs Wash 3          98.58        2             3.1462

Comparison              P<0.05
Wash 5 vs Wash 3        Yes
Wash 5 vs Wash 1        No
Wash 5 vs Wash 4        Do Not Test
Wash 5 vs Wash 2        Do Not Test
Wash 2 vs Wash 3        Yes
Wash 2 vs Wash 1        Do Not Test
Wash 2 vs Wash 4        Do Not Test
Wash 4 vs Wash 3        Yes
Wash 4 vs Wash 1        Do Not Test
Wash 1 vs Wash 3        Yes
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