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THE ORNL INDOOR AIR QUALITY STUDY: RE-CAP, CONTEXT, AND ASSESSMENT ON RADON

B. E. Tonn
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OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

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Environmental Sciences Division

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Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831-6283
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ACRONYMS AND ABBREVIATIONS

ACC	Activated Charcoal Canister
ACH	Air Changes per Hour
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
ATD	Alpha Track Detector
BPA	Bonneville Power Administration
CFM	Cubic Feet per Minute
EPA	Environmental Protection Agency
IAEA	International Atomic Energy Agency
IAQ	Indoor Air Quality
LCM	Low-cost Measure
ORNL	Oak Ridge National Laboratory
PERM	Passive Environmental Radon Monitor
WAP	Weatherization Assistance Program
Wx	Weatherization

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ABSTRACT

As part of the retrospective evaluation of the U.S. Department of Energy's low-income Weatherization Assistance Program that was led by Oak Ridge National Laboratory (ORNL), an assessment of the impacts of weatherization on indoor air quality (IAQ) was conducted. This assessment included nearly 500 treatment and control homes across the country. Homes were monitored for carbon monoxide, radon, formaldehyde, temperature and humidity pre- and post-weatherization. This report focuses on the topic of radon and addresses issues not thoroughly discussed in the original IAQ report. The size, scope and rigor of the radon component of the IAQ study are compared to previous studies that assessed the impacts of weatherization on indoor radon levels. It is found that the ORNL study is by far the most extensive study conducted to date, though the ORNL results are consistent with the findings of the other studies. However, the study does have limitations related to its reliance on short-term measurements of radon and inability to attribute changes in radon levels in homes post-weatherization to specific weatherization measures individually or in combination.

1. INTRODUCTION

As part of the retrospective evaluation of the U.S. Department of Energy's Weatherization Assistance Program (WAP) that was led by the Oak Ridge National Laboratory (ORNL), an assessment of the impacts of weatherization on indoor air quality (IAQ) was conducted. This assessment included nearly 500 treatment and control homes across the country. Homes were monitored for carbon monoxide, radon, formaldehyde, temperature and humidity pre- and post-weatherization. A complete description of the study and results can be found in Pigg et al. (2014).

Consistent with much of the existing literature on the effects of air sealing building envelopes on indoor radon levels, the ORNL IAQ study found, on average, a small, statistically significant increase in radon levels in weatherized homes post-weatherization. Like most of the other reports from the retrospective evaluation, the IAQ report mainly focused on describing the research methodology and presenting the results. The purpose of this report is to expound on topics not thoroughly discussed within the original IAQ report, including the strengths and deficits of the study (Section 3) and how the ORNL study situates amongst similar studies conducted over the past several decades (Section 4). Concluding statements are captured in the final section (Section 5). To set the stage for the balance of the report, the next section offers a brief summary of the ORNL study.

2. THE ORNL INDOOR AIR QUALITY STUDY

The data from the ORNL IAQ Study indicate that, on average, weatherization showed a small, statistically significant increase in radon levels in homes (Pigg et al. 2014).

The ORNL study was designed to assess the impacts of standard weatherization practices on radon levels in homes post-weatherization. All of the participating homes were part of a larger study of the impacts of weatherization on IAQ. As such, eligible WAP homes were randomly selected from a set of geographic areas located throughout the continental U.S. Homes located in the U.S. Environmental Protection Agency (EPA) Radon Zone 1 (highest potential) were oversampled to ensure enough homes in the sample had measurable levels of radon. The results were then weighted to the national WAP population of homes. Figure 1 contains a national map of the EPA radon zones and identifies the 35 sites (one site per state) from which houses were selected. Figure 2 contains a map that indicates the percentage of homes from all income levels predicted to exceed the EPA 4.0 pCi/L threshold.[1] The total number of homes in the study was 514, with 325 in the treatment group and 189 in the control group. All of these homes were in the queue to be weatherized. Homes were randomly selected to be in the treatment and control groups. Weatherization of the control homes was delayed until after this study was completed. The control homes were given an additional monetary incentive to agree to this arrangement to compensate for foregoing some energy cost savings while waiting somewhat longer to have their homes weatherized. It should also be noted that the control homes were located in the same geographical regions as the treatment homes in order to best control for weather, radon zone, climate zone, and housing type variables.

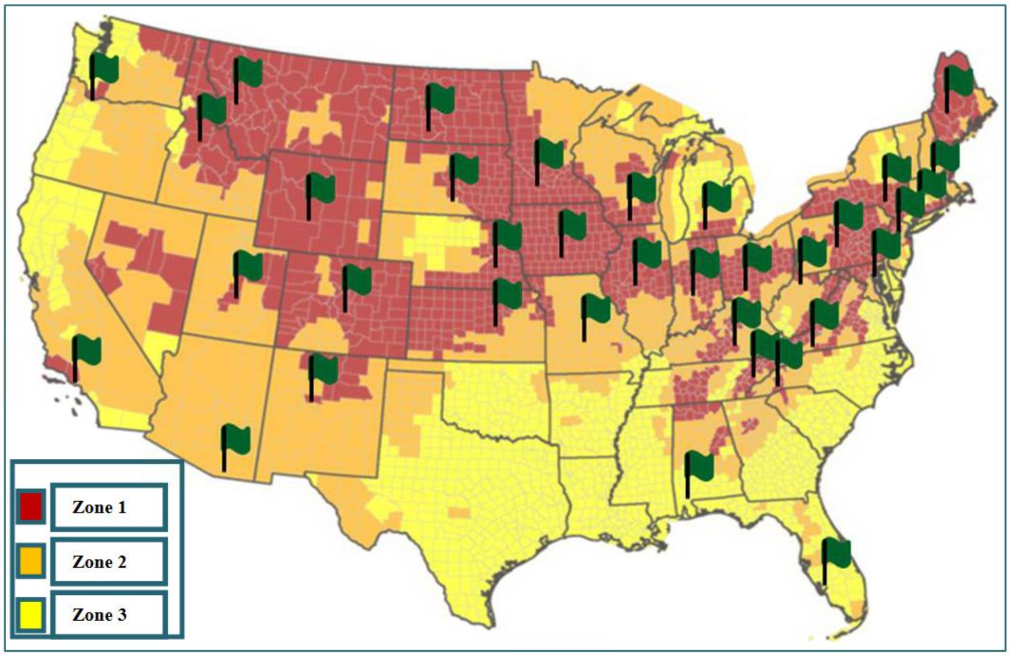

Figure 1. ORNL Radon Study States (35) and EPA Radon Zones (Pigg et al. 2014)

Radon levels were collected over a 7-day period pre- and post-weatherization using activated charcoal canisters (ACCs) provided by EPA. The EPA laboratory in Las Vegas, NV processed the canisters and

[1] It should be noted that this map does not distinguish between homes that are newer or older, or weatherized or not.

provided the ORNL study evaluation team with the measurement results. The data were collected over the winter during closed home conditions. The radon monitoring canisters were installed in the lowest occupied level of the house.[2] The treatment homes received standard energy audits, be they computer-based or guided by priority lists, and measures installed were guided by the audit results, savings-to-investment-ratio tests, etc. No weatherization practices were geared to specifically address radon. Table 1 presents selected characteristics of the two study groups and weatherization measures installed in the treatment homes, and also provides corresponding data for the larger WAP population[3].

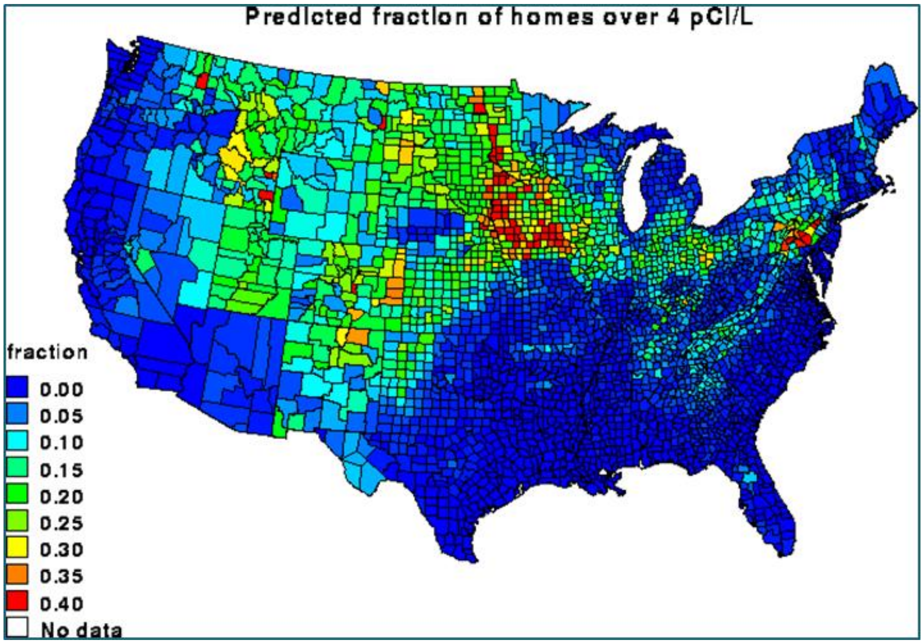

Figure 2. Predicted Fraction of Homes Over 4 pCi/L (LBNL 2015)

[2] In a house with a typical basement, the ACC would have been installed in the floor above the basement. The ACC was installed in the basement only if the basement was finished living space.

[3] Primary differences: more wall and other insulation, more exhaust fans, and higher costs in IAQ homes.

Table 1. Selected Weatherization Measures Installed in Both Study Samples (weighted) and WAP Population

	Pooled groups (n=514)	Treatment group (n=325)	Control group (n=189)	PY08 SF population†
Air Leakage (CFM50)[4]				
Pre-weatherization	3,227 ±267	3,306 ±316	3,096 ±356	3,533 ±61
Post-weatherization		2,291 ±180		2,314 ±45
Insulation				
Attic		67% ±7		58% ±2
Wall		19% ±6		7% ±1
Other		47% ±7		23% ±1
Heating system replacement				
For energy savings		19% ±5		12% ±1
For health and safety		9% ±4		12% ±1
Water heater replacement				
For energy savings		6% ±3		3% ±1
For health and safety		3% ±2		6% ±1
Setback thermostat		11% ±5		10% ±1
Ventilation				
Exhaust fan		29% ±8		13% ±1
Whole house ventilation		2% ±2		<1%
Health & safety				
CO detector		70% ±9		56% ±2
Smoke alarm		50% ±10		46% ±2
Mean weatherization cost (All funding sources)		$4,580 ±490		$3,300 ±100

†Estimated from other (DF-2) evaluation data for single-family homes (site-built and manufactured). Excludes Alaska and Hawaii.
± Values are approximate 90% confidence intervals.

Table 2 presents a summary of descriptive statistics on radon levels pre- and post-weatherization in treatment and control homes by radon zone and housing type (i.e., single-family site-built and mobile homes). These results indicate that on average, over a set of several hundred homes, weatherization is associated with higher levels of radon post-weatherization. The results further indicate that:

- Radon increases due to weatherization are limited, on average, to single-family site-built homes as opposed to mobile homes;
- On average, radon increases are statistically significant only in homes located in Radon Zone 1.
- Impacts from WAP are higher in homes that contain high levels of radon pre-weatherization (i.e., homes testing below 10 pCi/L pre-weatherization had a net radon increase of 0.16 pCi/L lower than homes that tested higher than that level).

It should be noted that the radon levels in the control group decreased during the period when the treatment homes were monitored for radon post-weatherization. One possible explanation is that ambient temperatures were gradually increasing during the end of the winter period, and subsequent regression models (see below) indicate that radon levels decrease as ambient temperatures increase (possibly because of reduced stack effect drawing less radon into the house as ambient temperatures increase). The

[4] CFM stands for cubic feet per minute.

change in the control group radon value is not fully understood and yet plays a dominant role in the net values.

Table 2. Net change in Radon Level, by EPA Zone and Housing Type (arithmetic means)

	N	Pre-weatherization, pCi/L Treatment Group (n=285)	Pre-weatherization, pCi/L Control Group (n=162)	Change (Post – Pre), pCi/L Treatment Group	Change (Post – Pre), pCi/L Control Group	Change (Post – Pre), pCi/L Net (Treatment – Control)
Overall						
All cases	447	2.0 ±0.3	1.9 ±0.3	+0.14 ±0.13	-0.29 ±0.18	+0.44 ±0.18
Pre-Wx* radon <10 pCi/L	438	1.6 ±0.2	1.7 ±0.3	+0.11 ±0.12	-0.16 ±0.12	+0.28 ±0.14
By EPA radon zone						
High (Zone 1)	234	2.4 ±0.4	2.7 ±0.5	+0.29 ±0.18	-0.50 ±0.33	+0.79 ±0.31
Moderate (Zone 2)	170	2.3 ±0.6	1.4 ±0.3	+0.10 ±0.26	-0.11 ±0.25	+0.23 ±0.28
Low (Zone 3)	43	0.6 ±0.2	0.8 ±0.3	-0.10 ±0.14	-0.11 ±0.13	+0.01 ±0.20
By Housing Type						
Site-built	362	2.4 ±0.3	2.3 ±0.3	+0.24 ±0.16	-0.44 ±0.21	+0.68 ±0.24
Mobile home	85	0.8 ±0.2	0.6 ±0.1	-0.13 ±0.16	+0.20 ±0.24	-0.33 ±0.29
Site-built homes in high potential counties (Zone 1)	192	2.8 ±0.4	3.3 ±0.6	+0.46 ±0.21	-0.62 ±0.45	+1.08 ±0.42

*Weatherization (Wx)
Results are weighted to reflect the population of single-family homes treated by WAP in PY08.
Results below detection limit (0.5 pCi/L) set to 0.25 for calculation purposes.
± Values are approximate 90% confidence intervals.

Table 3 presents two regression models that attempt to explain variations in radon levels in the treatment homes post-weatherization. These results indicate that:

- Decreases in air changes per hour (ACH) as measured with a blower door test at 50 Pascals are statistically related to increases in radon levels post-weatherization.
- The presence of continuous mechanical ventilation is related to decreases in radon.
- The significance of the two weather related variables, precipitation and temperature, speak to the diurnal, weekly, and seasonal variability observed in radon levels.
- The statistical significance of the non-continuous ventilation variable requires additional assessment.

Table 3. Model of Post/Pre Radon Level

Dependent variable: $Radon_{post}/Radon_{pre}$ (pCi/L, above-grade test result)

Run 1: all cases included

	Coefficient	t-statistic	
$ACHnat_{pre}/ACHnat_{post}$	0.188	2.34	**
Change in outdoor temperature, °F	-0.00877	-3.52	***
Change in fraction of days with precipitation during test period	-0.422	-2.71	***
Mobile home (binary)	-0.0864	-0.85	
Ground cover added to site-built home (binary)	0.114	1.16	
Below grade sealing for site-built home (binary)	-0.00982	-0.13	
Continuous mechanical ventilation added (binary)	-0.254	-2.12	**
Non-continuous mechanical ventilation or dryer venting added (binary)	0.189	2.12	**
Heating system replaced w/ sealed combustion model (binary)	0.283	-0.85	
model constant	0.774	7.31	***

Regression statistics: n=236; adjusted r^2 = 0.135; F statistic = 5.06

Run 2: restricted to 0.3 < $Radon_{post}/Radon_{pre}$ < 3.0 (8 cases dropped)

	Coefficient	t-statistic	
$ACHnat_{pre}/ACHnat_{post}$	0.220	3.44	***
Change in outdoor temperature, °F	-0.009	-4.66	***
Change in fraction of days with precipitation during test period	-0.192	-1.51	
Mobile home (binary)	-0.193	-2.33	**
Ground cover added to site-built home (binary)	0.0676	0.86	
Below grade sealing for site-built home (binary)	0.0141	0.23	
Continuous mechanical ventilation added (binary)	-0.224	-2.36	**
Non-continuous mechanical ventilation or dryer venting added (binary)	0.0188	0.26	
Heating system replaced w/ sealed combustion model (binary)	0.0307	0.36	
model constant	0.788	9.32	***

Regression statistics: n=228; adjusted r^2 = 0.114; F statistic = 4.25

**Statistically significant at a 95% confidence level
***Statistically significant at a 99% confidence level

A 7-day pre- and post-weatherization monitoring period was used to measure radon in the ORNL IAQ study. One question is whether such short-term tests can capture the variability in radon levels month-to-month and, therefore, can they be completely relied upon to: 1) determine whether a home exceeds the annual mean 4.0 pCi/L threshold, and 2) estimate weatherization's affect on radon levels post-weatherization.

One study, Barros (et al. 2014), has been cited to support the contention that short-term tests are appropriate to address these two points. The Barros study analyzes data collected in the mid-1990s in Iowa in homes that have high levels of radon (~5.0 pCi/L). The study compares 7-10 day radon tests collected in winter in closed home conditions with annual measurements made in the same homes.

- The study concludes that the results of the short-term tests are highly correlated with the long-term tests.
- However, the results do not suggest the results from the short-term tests equate to the results from the annual measurements.

This is seen in two ways. First, the short-term tests over-estimate radon levels by 0.48 PCi/L, which is 9% higher than the long-term radon levels measured in the houses in their study. Second, the paper states that given the results of the short-term test, a homeowner could be 95% confident that radon levels are below 4.0 pCi/L if the short-term results are 3.29 pCi/L or lower and 95% confident that the radon levels are above 4.0 pCi/L if the results are 5.78 pCi/L or higher.

Applying these two observations to the interpretation of the ORNL IAQ study results provides several preliminary, but interesting insights. Applying a downward adjustment of 0.48 pCi/L reduces the number of treatment homes that apparently moved from below the EPA threshold to above the threshold post-weatherization (from 4.1% to 3.2%) (see Table 4). In 86.2% of the treatment homes, either the post-weatherization radon levels remained less than EPA's action limit of 4.0 (81.2%) or were reduced from above the action limit to below the action limit (5%). In 9.6% of homes, the pre-weatherization value was greater than the action limit and remained so following weatherization. In only 4.1% of the homes did weatherization cause the home to go above the action limit when it was below the limit before weatherization. Finally, of the 13.7% (9.6% + 4.1%) of the homes still testing over the threshold post-weatherization in the ORNL sample, one could be 95% sure that the home really did exceed that threshold given uncertainties in the short-term test in only 1 in 9 homes (or only 1.5% of the total homes) (see Table 5).

Table 4. Treatment Only, Pre-Post % with Respect to 4.0 pCi/L

	-/-	+/+	+/-	-/+
Unadjusted	81.2	9.6	5.0	4.1
Subtract .48	84.4	8.3	8.3	3.2
Subtract 9%	83.5	8.3	5.0	3.2

Table 5. Treatment Only, Post Only, Sure with Respect to 4.0 pCi/L

	95% certain -	95% certain +	Uncertain – or +
Unadjusted	79.4 (173)	6.4 (14)	14.2 (31)
Went from – to +		11.1 (1)	88.9 (8)
Went from + to –	63.6 (7)		36.4 (4)
Went from – to –	93.8 (166)		6.2%(11)
Went from + to +		61.9(13)	38.1(8)

3. ORNL IAQ STUDY STRENGTHS AND LIMITATIONS

Similar to almost all research studies, the ORNL IAQ study has strengths and limitations. As will be shown in more depth in the next section, the study represents the most comprehensive assessment of the relationship between low-income weatherization and indoor radon levels ever conducted. The number of homes in the study is an order of magnitude higher than any previous study. The size of the sample adds unprecedented statistical power to the analyses. The sample of single-family and mobile homes is representative of the WAP population in general and also by climate zone and radon zone. The demographics of the participating households are comparable to the demographics of the larger population of WAP recipients.

In the most recent (2013) review of methodology and measurement techniques put forth by the International Atomic Energy Agency (IAEA), ACCs are recommended as suitable devices for *screening* purposes. ACCs can provide short-term measurements for indoor radon levels, but should then be followed up with a long-term measurement technique (e.g., alpha track detectors (ATDs)) for confirmation. Because ACCs are a short-term measurement device, they provide an efficient and low-cost method for “quickly identifying dwellings with a potential for high radon concentrations” (IAEA 2013). The IAEA classified ACCs as a “non-suitable” technique for measuring the annual average radon concentration in dwellings.

Even if one were to accept the ACC device results as a valid measure of long-term radon exposure within the homes sampled, the ORNL IAQ study only offers limited insights into building science issues related to weatherization and radon. The study finds that weatherization is correlated with higher radon levels post-weatherization. The study finds that air sealing may be one contributor, but this is not a new or unique finding. The study also finds that radon increases are larger in magnitude in homes that had very high levels of radon pre-weatherization.

The ORNL IAQ study is not capable of isolating the impacts of specific individual weatherization measures or combinations of weatherization measures on radon increases or decreases post-weatherization. The regression models in Table 3 indicate that air sealing is positively correlated with radon increases and continuous ventilation is negatively correlated. However, the models do not explain the preponderance of variation in the data. Data available did not allow the exploration of the impact on radon of individual air sealing measures, such as air sealing attics or doors and windows versus air sealing ducts, nor allow the assessment of synergistic impacts of various air sealing measures, various combination of insulation measures, and specific ventilation solutions in specific locations.

The ORNL IAQ study also cannot provide any insights into the impacts of additional low-cost measures that could mitigate radon levels post-weatherization (e.g., well installed vapor barriers, caulking of cracks in concrete in basements and crawlspaces), either individually or in combination. The ORNL IAQ study was conducted before WAP adopted the new American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) 62.2 ventilation guidelines, which precluded the collection of an extensive amount of data that could have provided better insights into the impacts of the addition of continuous ventilation on radon levels post-weatherization. However, a small follow-on study conducted in about a dozen homes did indicate that ASHRAE 62.2 ventilation solutions can mitigate radon levels post-weatherization (Pigg 2014a).

The building science phenomena related to weatherization and radon could be more complex than originally thought. The ORNL IAQ study was developed under that assumption that radon’s infiltration into homes is continuous, or at least that the occurrence of episodes where radon levels spike in homes was not an important topic to study. For example, the radon canisters used were only able to indicate the amount of radon they were exposed to over a seven-day period rather than indicate how radon levels may have varied from day-to-day and hour-to-hour. It can be argued that this perspective also implicitly assumes that radon increases are linearly correlated with increases in the air tightness of homes.

An alternative assumption that should be considered is the possibility that radon levels and ACH are non-linearly related. From this perspective, one should imagine a home that has repeated spikes in radon levels, which is common and is illustrated for example in Figure 3. The rate at which radon is evacuated from the home is related to its baseline air change rate. In a home with a high air change rate, the radon spike could be evacuated in a matter of hours. In a home with a very low air change rate, it may take days to expel the radon spike. In that time period, another radon spike may occur, thereby compounding radon levels and producing a non-linear relationship between radon and air change rates.[5]

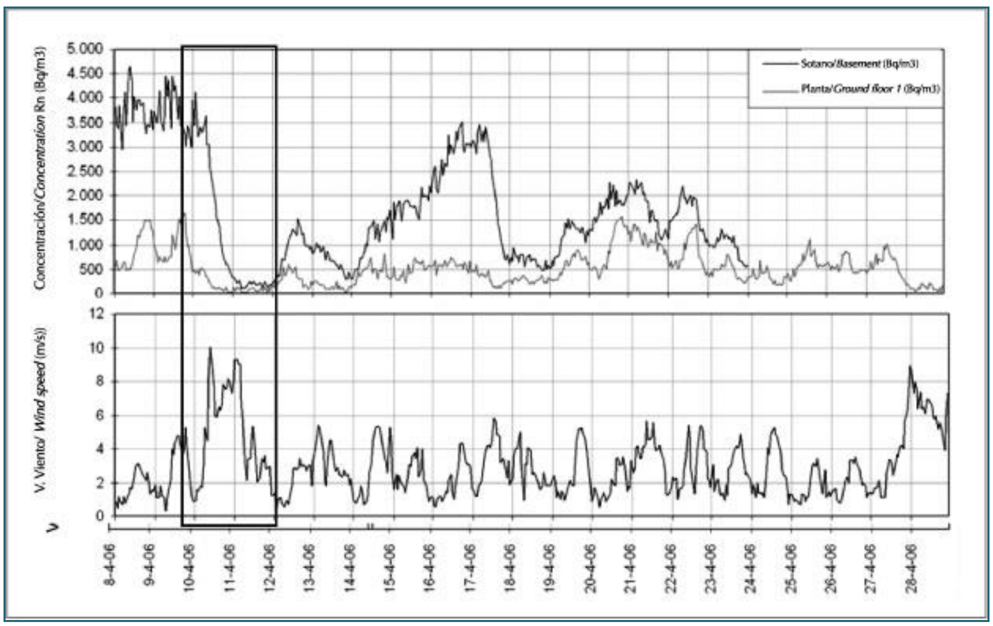

Figure 3. ACH and Concentration of Radon Levels (Vázquez et al. 2001)

[5] This perspective was put forth by Dave Wilson, an ORNL radon expert, based on his experiences in testing for radon in U.S. military housing (Personal communication).

If this hypothesis is correct, then there is a threshold level of baseline air changes per hour where the non-linear impacts of weatherization would begin.[6] The data collected by the ORNL IAQ study do not show non-linear relationships between ACH and radon levels (see Figures 4 and 5), though it can be argued that even post-weatherization the new ACH levels in the WAP weatherized homes are too high to trigger the non-linear impacts. If such a level could be determined with some accuracy, then weatherization procedures could be developed to not allow ACH in homes to dip below the threshold.[7]

The ORNL IAQ study's data and analyses are not capable of allowing an auditor to predict radon changes in a specific home resulting from the installation of any specific measure or combination of measures. As mentioned above, this is due in part to a lack of granularity in the data to associate specific measures or combinations of specific measures to estimated changes in radon. It is also due in part to measurement issues associated with the study. As noted above, there are measurement error issues associated with the ACCs, issues that could be addressed by using more accurate technologies deployed for longer periods of time.

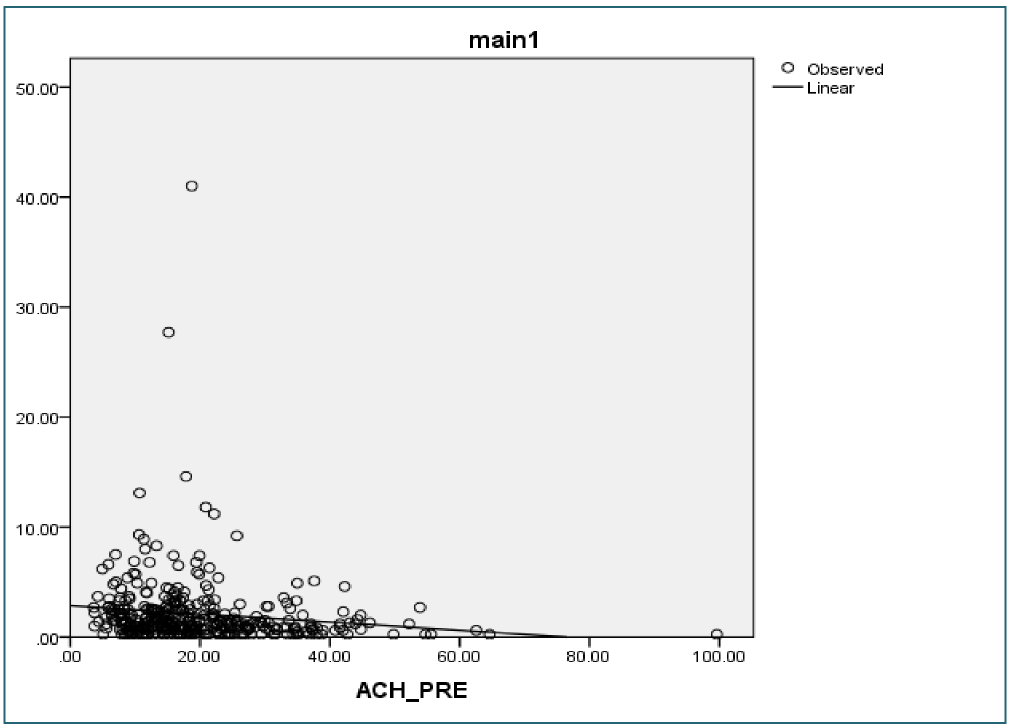

Figure 4. Relationship Between ACH and Radon Levels Pre-Weatherization

[6] In discussions with Wilson, the threshold could be in the range of 0.1 to 0.3 ACH.
[7] Making homes too tight is not just a radon issue, according to Wilson. Occupants, when power goes out, may use unvented kerosene heaters or "Buddy" heaters. In really tight homes, the occupants may run the risk of CO poisoning.

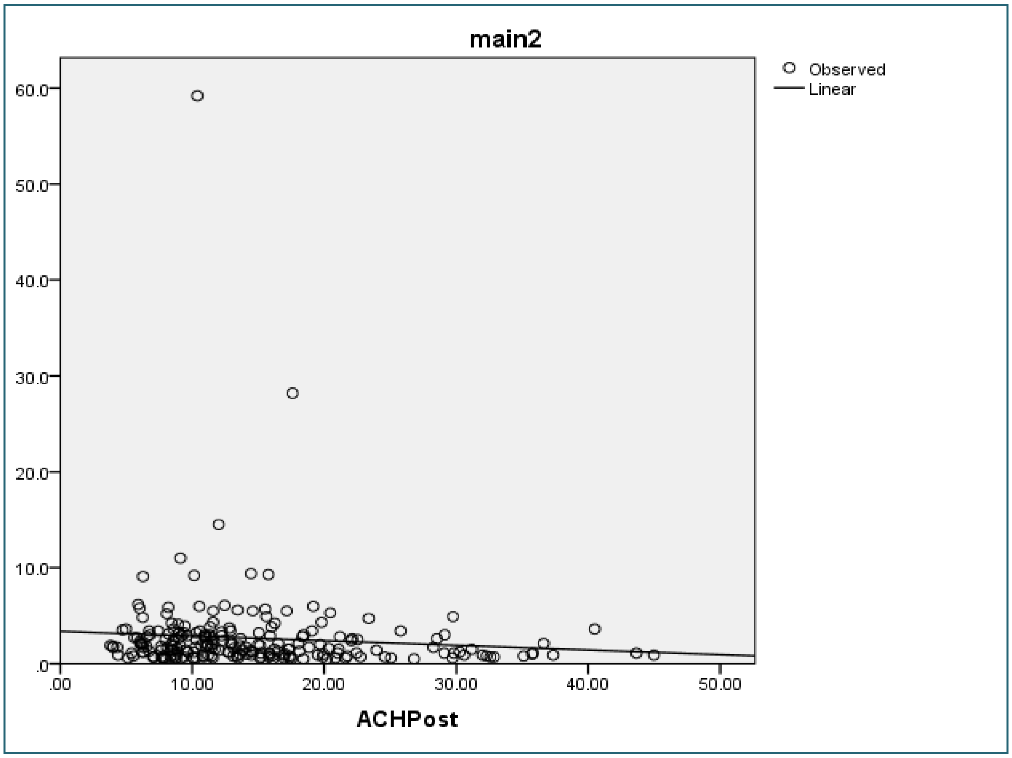

Figure 5. Relationship Between ACH and Radon Levels Post-Weatherization

It is important to make a distinction between measured radon levels and an occupant's exposure to radon. The ORNL IAQ study's design may have led to an overestimate in the measured levels of radon. Certainly, the closed home conditions in the winter, under which the study was conducted, would lead to higher radon measurements than would have been the case had data been collected for months or over a year.

Also, the study is not able to assess how much radon occupants would be exposed to post-weatherization. One can argue that the measured level of radon overestimates human exposure to radon. For example, it is very unlikely that occupants would be exposed to radon levels as measured in the lowest living area, especially if that area was a basement. This is because occupants spend significant time out of their homes and in rooms of their homes that plausibly have lower levels of radon (e.g., second floor bedrooms). The study did not collect radon measurements in multiple rooms throughout the homes nor any data on how much time individuals spend in each room and out of the house.

The literature states that it takes decades of exposure to radon to result in human health impacts (e.g., lung cancer). It is known that the composition of household members in low-income households can be quite fluid at times (Pigg 2014b; Tonn, Rose, and Hawkins 2014). In addition, households of lower socioeconomic status are more likely to experience residential disruption (i.e., frequent mobility) for a myriad of reasons. This makes it difficult to estimate the impacts on human health from periodic exposures to potentially higher levels of radon for the WAP income eligible population.

Table 6 contains a summary of the ORNL IAQ study's strengths and limitations.

Table 6. Summary of the ORNL IAQ Study's Key Strengths and Limitations

ORNL IAQ Study Finding- Strengths
The sample of single-family and mobile homes is representative of the WAP population in general and also by climate zone and radon zone. The demographics of the participating households are comparable to the demographics of the larger population of WAP recipients.
The experimental design of the ORNL IAQ study offers statistically defensible and generalizable results attributable to WAP impacts on dwellings during closed-home winter conditions.
ORNL IAQ Study Finding- Limitations
Short-term ACC devices were deployed as the only instrument to measure radon levels. No long-term monitoring was conducted to determine valid mean annual radon values.
The study is unable to adequately explain the change in radon levels in the control group beyond change in ambient temperature. This is critical as the net change in radon values post-weatherization is dependent on the change in the mean control group value.
The study is not capable of isolating the impacts of specific individual weatherization measures or combinations of weatherization measures on radon increases or decreases post-weatherization.
The study cannot provide any insights into the impacts of additional low-cost measures that could mitigate radon levels post-weatherization either individually or in combination.
The study cannot provide any insights into the potential differences between measurements of and long-term exposure to radon.

4. THE ORNL IAQ STUDY IN CONTEXT OF THE EXISTING LITERATURE

The findings generated from the ORNL IAQ study will contribute to the existing and building body of literature related to home energy efficiency and indoor radon exposure. The ORNL study reviewed seven relatable research papers as a means for comparing findings (see Figure 6). Most studies agree with ORNL results in that small, statistically significant increases in radon are observed, on average, following weatherization. Each of these studies is summarized below. At the end of each summary, the following information is provided: Sample Size; Climate Zone – Cold, Moderate, or Hot; Radon Zone – 1 (highest potential), 2 (moderate potential), or 3 (low potential); and Population Type – Low-Income, Non Low-Income, or Unknown.

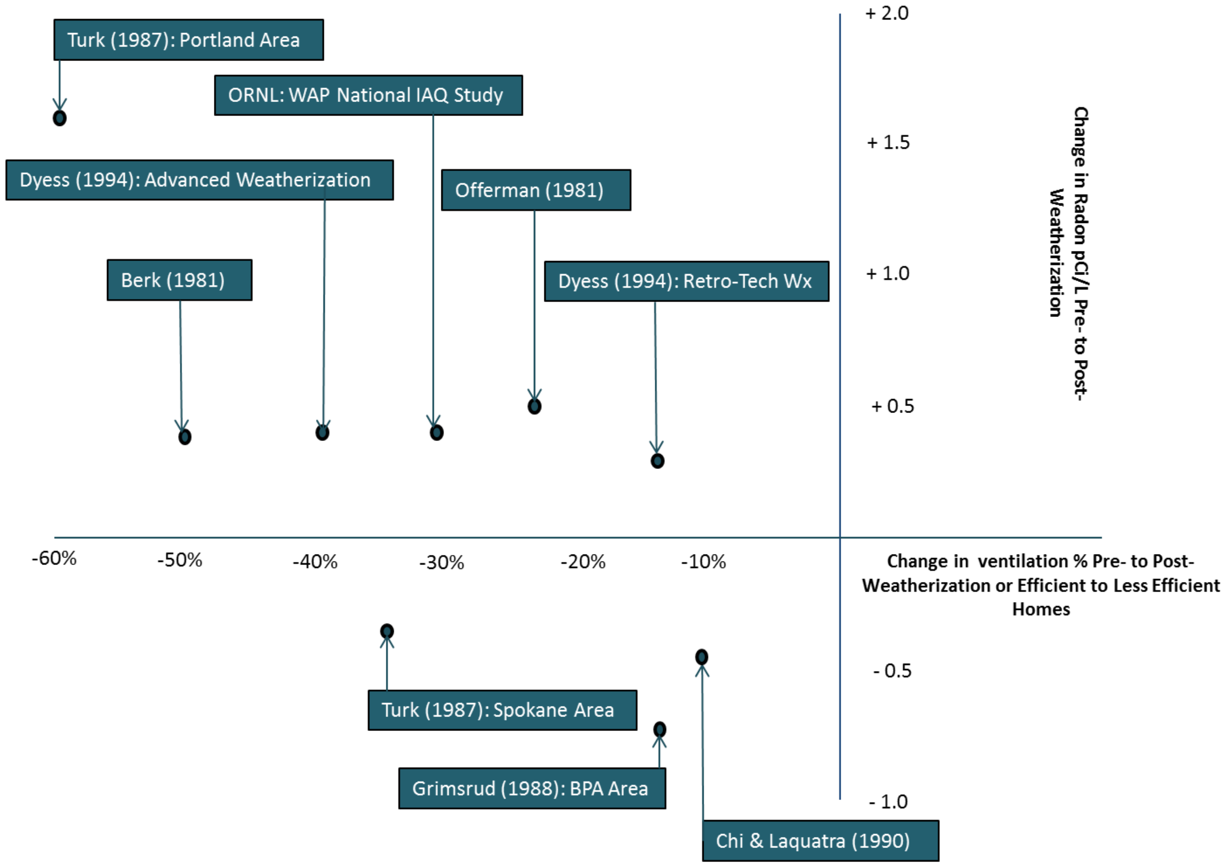

Figure 6. Findings Related to Change in Radon Levels as a Result of Change in Ventilation Pre- to Post-Weatherization for the ORNL Radon Study Compared to Relatable Studies

(1) *Berk (1981)* – This study employed a mobile laboratory equipped to measure indoor contaminants. Of the eleven homes in the study, only one had usable radon measurements pre- and post-weatherization. Weatherization consisted of: storm windows and doors; weather stripping; ceiling, floor, and duct insulation; and ground cover/moisture barriers. This home was located in Medford, Oregon, in a low radon zone. The pre-weatherization radon measurement was < 1.0 pCi/L and the post-weatherization measurement was 1.2 pCi/L. These measurements were collected during warm spring and summer months, given an approximately 50% decrease in ventilation. A Passive Environmental Radon Monitor (PERM) was used to collect the radon data. The study ascribes only a slight increase in radon to weatherization. (Sample Size = 1; Climate Zone = Moderate; Radon Zone = 3 (low potential); Population Type = Unknown)

(2) *Offerman (1981)* – This study assessed 12 homes pre- and post-weatherization located just outside of Richland, Washington, in a moderate radon zone. Radon was measured using PERM devices. Data were collected for one week pre- and one week post-weatherization. The pre-weatherization average radon level was 1.2 pCi/L, and the radon level increased 0.5 pCi/L post-weatherization, given a 23% reduction in ventilation. The author noted that this result is not unexpected given the increase in air tightness of the homes, but also qualified his results by noting that different air sealing measures could impact radon differently. He also noted that when one of the houses was exhausting air from the house, post-weatherization, radon levels dropped over 2.0 pCi/L. (Sample Size = 12; Climate Zone = Moderate; Radon Zone = 2 (moderate potential); Population Type = Unknown)

(3) *Fleischer et al. (1982)* – This research surveyed 27 solar/energy efficient homes and conventional homes located in northeastern New York state in low and moderate radon zones. Respondents' subjective judgments were used to categorize homes as energy efficient or conventional. ATDs were used to collect the radon data. No data were collected regarding weatherization measures, the air tightness of the homes, or other levels of energy efficiency. The lack of ventilation data makes it not possible to situate this study with the other studies. However, the solar/energy efficient homes were found to have higher levels of radon (radon levels measured in the basement for a full year averaged 1.33 pCi/L in the conventional homes and 6.0 pCi/L in the solar/energy efficient homes). The authors did note that the solar homes contained significant amounts of heat-storage materials that could be a source of radon. (Sample Size = 27; Climate Zone = Cold; Radon Zone = 2 (moderate potential) and 3 (low potential); Population Type = Non Low-Income)

(4) *Turk et al. (1987)* – This study assessed radon in 61 new homes located in two regions of the Pacific Northwest (Portland, OR and Spokane, WA) that cover all three radon zones. Twenty nine homes were built to Model Conservation Standards, and 32 were control homes. Radon was monitored using a Terradex Type SF passive sampler from 55 to 70 days in each house. Two to five samplers were deployed in each house. This study measured an average radon increase of about 1.5 pCi/L post-weatherization in the homes located in the Portland region, and a decrease of about 0.4 pCi/L in the Spokane homes. "Indoor pollutant concentrations were observed to be only poorly correlated with ventilation rates" and "were seen to vary more between geographic regions than between the two types of house construction." This study is interesting in that it makes a distinction between air tightness as measured by a blower door test and ventilation as measured by a perfluorocarbon tracer system. The later shows much less air movement in homes, possibly meaning much less movement of radon gas from one part of a home to another. (Sample Size = 61; Climate Zone = Moderate; Radon Zone = 1 (highest potential), 2 (moderate potential), and 3 (low potnetial); Population Type = Non Low-Income)

(5) *Grimsrud (1988)* – This research studied 48 homes (40 weatherized, 8 control, plus five with additional house doctoring) in the Bonneville Power Administration (BPA) region (Vancouver and Spokane, WA) that covered all three radon zones. Homeowners were mailed the ATD testing kits, with most being installed in the homes between 21 to 35 days. The standard BPA

weatherization reduced air leakage by 12.5%, and the house doctoring added an additional 26% reduction. Radon levels decreased post-weatherization for this sample by about 0.7 pCi/L on average. (Sample Size = 48; Climate Zone = Moderate; Radon Zone = 1 (highest potential), 2 (moderate potential), and 3 (low potential); Population Type = Unknown)

(6) Chi and Laquatra (1990) – This study assessed radon levels in 245 randomly selected representative households in nonmetropolitan counties in central and western New York State. The homes were in a high radon zone. Homes were graded on a 0-6 point scale on existing weatherization measures (i.e., on existing energy efficiency levels) in the homes. Ventilation rates were not measured. Radon levels were measured in closed home conditions using ACCs, deployed for one week. The weatherization scale was regressed against the radon dependent variable, controlling for local soil types and space heating systems. The regression results suggest a negative, though not quite statistically significant relationship between weatherization and radon levels (i.e., the more energy efficient the home, the lower the radon level would be). (Sample Size = 245; Climate Zone = Cold; Radon Zone = 1 (highest potential); Population Type = Low-Income and Non Low-Income)

(7) Dyess (1994) – This study assessed 28 WAP homes in Maryland pre- and post-weatherization. Three groups of homes were in the study: homes that received standard weatherization measures at the time, homes that received additional weatherization measures, and homes that received no weatherization (i.e., controls). ATDs were used to measure radon for 30-45 days. Ventilation was measured pre- and post-weatherization. The author concludes that "… the data generally suggest that weatherization procedures did not adversely affect indoor radon levels." (Sample Size = 28; Climate Zone = Moderate; Radon Zone = 1 (highest potential), 2 (moderate potential), and 3 (low potential); Population Type = Low-Income)

Not all seemingly relatable research studies studying home energy efficiency and radon can or should be compared to the ORNL IAQ study. The ORNL study offers statistically defensible results that can be generalized to the WAP eligible population residing in single-family site-built or mobile homes across all EPA radon zones in the continental U.S. In efforts to situate the ORNL study amongst other relatable studies, evaluation criteria were developed to better distinguish which studies are indeed fair to compare:

- *Weatherization Impact* – The study is capable of assessing whether the relationship between changes in radon levels pre-weatherization to post-weatherization is dependent upon the pre-retrofit radon levels (10) versus not (0).
- *Measuring Radon Episodes* – The radon collection approach is capable of collecting radon data on an hourly basis over a period of time (10) versus only able to collect the aggregate amount of radon emitted over the period of time (0).
- *Uniqueness of Data* – Data collected are unique (10) versus simply adding to an existing data set or providing more data points to complement existing studies (0).
- *Representativeness of Homes* – The study encompasses a set of homes that is representative of the homes receiving WAP services (i.e., housing types, climate zones, existing homes, radon zones) (10) versus a set of homes that is not representative of WAP homes (e.g., new homes located only in a low radon zone) (0).
- *Representativeness of Households* – The study encompasses a set of households that is representative of WAP households (i.e., low-income, full range of occupant demographics) (10) versus a set of households that is not representative of WAP households (e.g., non low-income homes occupied only by young families) (0).

- *Statistical Power* – The number of homes in the study and the amount of data collected are sufficient to draw statistically defensible conclusions (10) versus the number of homes in the study is too small to draw any statistically defensible conclusions (0).
- *Generalizability* – The study results are generalizable to the WAP context (i.e., existing homes, house types, climate zones, low-income households and typical WAP recipients) (10) versus not being generalizable to WAP (i.e., new homes, unrepresentative climate zone, non-low-income population) (0).
- *Building Science (Weatherization*) – The study is capable of isolating the synergistic relationships between standard weatherization measures and radon increases post-weatherization (10) versus not being able to attribute changes in radon to any specific measure or subsets of measures (0).
- *Building Science (Low-Cost Measures (LCMs))* – The study is capable of isolating the synergistic relationships between additional low-cost weatherization or remediation measures that may mitigate radon levels and radon levels post-weatherization (10) versus not studying the impact of low-cost weatherization or remediation measures (0).
- *Building Science (Ventilation)* – The study is capable of estimating the impact of ASHRAE 62.2 ventilation solutions (10) versus no ventilation incorporated (0).
- *Human Exposure* – The study is capable of estimating the actual exposure of occupants to radon pre- and post-weatherization (10) rather than assuming that occupants will be fully exposed every hour of every day to the amount of radon measured in the lowest living level of their home (0).
- *Measurement Instrument* – The study is able to provide insights into variations in radon levels in homes pre- and post-weatherization for a range of seasons and conditions (10) versus not being able to provide insights into such variations (0).
- *Testing Existing Theory* – The data collected has the potential to test the hypothesis that there is a non-linear relationship between ACH and radon levels (e.g., if ACH drops below 0.3 then radon levels exponentially increase) (10) versus the data do not allow testing of this theory (0).

According to the scores using the selected criteria (see Tables 7 and 8), the most relatable and comparable study conducted, to date, is the research collected through the Dyess study (1994) followed by the studies conducted by Chi and Laquatra (1990), Turk et al. (1987), Offerman (1981), and Grimsrud (1988). The Berk (1981) and Fleischer et al. (1982) studies lack representativeness of the WAP housing and eligible population, or ability to be generalized to WAP.

Table 7. Scoring Assessment of Comparable Studies to the ORNL IAQ Study									
Scoring Criterion (0-10) (10= most ideal)									
Study Identifier (Ordered by date)	Weight	1	2	3	4	5	6	7	WAP
Weatherization Impact	x2	10	20	0	0	20	5	20	20
Measuring Radon Episodes	-	0	0	0	0	0	0	0	0
Uniqueness of Data	x2	20	20	20	20	20	20	20	20
Representativeness of Homes	-	0	5	0	5	5	5	5	10
Representativeness of Households	-	0	5	0	5	10	5	10	10
Statistical Power	x2	0	0	10	10	10	20	10	10
Generalizability	x2	0	10	0	10	10	20	10	20
Building Science (Wx)	-	0	5	0	5	5	5	5	5
Building Science (LCMs)	-	0	0	0	0	0	0	0	0
Building Science (Ventilation)	-	0	5	0	10	0	0	5	10
Human Exposure	x2	10	10	10	10	10	10	10	10
Measurement Instrument	x2	10	10	20	20	10	10	15	10
Testing Existing Theory	-	0	0	0	0	0	0	0	0
Total (out of 170)		**50**	**90**	**60**	**95**	**90**	**95**	**110**	**125**

Table 8. Relatable Studies to the ORNL IAQ Study by Tiers				
Relatable Study (Ordered by most comparable)	Total Score	Tier 1	Tier 2	Tier 3
7	110	X		
6	95		X	
4	95		X	
2	90		X	
5	90		X	
3	60			X
1	50			X

5. CONCLUSIONS

The ORNL IAQ study is the most extensive study of the impacts of weatherization on indoor air quality of low-income homes ever conducted. The retrospective evaluation report (Pigg et al. 2014) presented results in a number of areas, including radon. The purpose of this report is to enrich discussions about the radon component of the ORNL IAQ study.

It is quite clear that the radon component of ORNL's IAQ study encompassed an unprecedented sample size and geographic distribution. It also implemented a rigorous random control trial study design. No other studies are comparable in size, scope or rigor. On the other hand, the ORNL study results are similar to those of the other studies. In other words, the radon increases measured post-weatherization by the ORNL study fall essentially in the middle of the findings from the other studies.

Despite its size, scope and rigor, the ORNL study has several limitations. First, it was not able to estimate the long-term changes in radon levels post-weatherization because it relied on short-term tests. Second, even with the large sample size, it was not possible to attribute changes in radon levels post-weatherization to specific weatherization measures. Third, the study was conducted to assess the impacts on IAQ of standard weatherization practices at the time. Therefore, no provisions were made to study the potential mitigating impacts of low-cost measures installed specifically to deal with radon. Also, the study was not able to collect data on the potential mitigating impacts of the ASHRAE 62.2 standard, though a very small follow-up study (Pigg 2014a) suggests this potential might exist. Lastly, like all of the other studies reviewed, no attempt was made to measure human exposure to radon as opposed to radon levels in a pre-specified location in the home. All of these limitations are addressable through additional research.

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