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Comparing the acoustical nature of a compressed earth block (ceb) residence to a wood-framed residence

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Innovations using Compressed Earth Block (CEB) have been developed and researched over the past few decades and recently the focus for a collaborative team of faculty and students at a The University of Oklahoma (OU) College of Architecture (CoA), OU's College of Engineering (CoE), and Norman, Oklahoma's Cleveland County Habitat for Humanity (CCHFH). The multidisciplinary research project resulted in the design and simultaneous construction of both a CEB residence and a conventionally wood-framed version of equal layout, area, volume, apertures, and roof structure on adjacent sites. Researchers sought to demonstrate the structural, thermal, economical, and acoustical value of CEB as a viable residential building material. This article defines field gathered ambient Noise Criteria (NC) levels, Noise Isolation Class (NIC) with charted frequency responses, and Fast Fourier Transform (FFT) acoustical measurements of both residences prior to occupancy using Real Time Analyzing equipment, with plans to further explore these values, Outside-Indoor Transmission Class (OITC), and Field Sound Transmission Class (FSTC) compared to laboratory Sound Transmission Class (STC) and Transmission Loss (TL) values.

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PROJECT BACKGROUND

Faculty and students at The University of Oklahoma (OU) College of Architecture (CoA) and College of Engineering (CoE) initiated and completed two adjacent single-family residences (context defined in Figure 1) in partnership with Cleveland County Habitat for Humanity (CCHFH). One residence was constructed primarily from Compressed Earth Block (CEB) while the other employed conventional 2x4 wood-framed construction to be the control residence. Both residences share equal interior layout, area, volume, apertures, and roof structure for the purpose of comparing exterior loadbearing materials. The multi-disciplinary collaborative research project embodies the process of determining CEB as an affordable, safe, and environmentally friendly residential building material. The relationship with CCHFH began Spring 2011 as a model for data collection and comparison with completed residences Summer 2014.

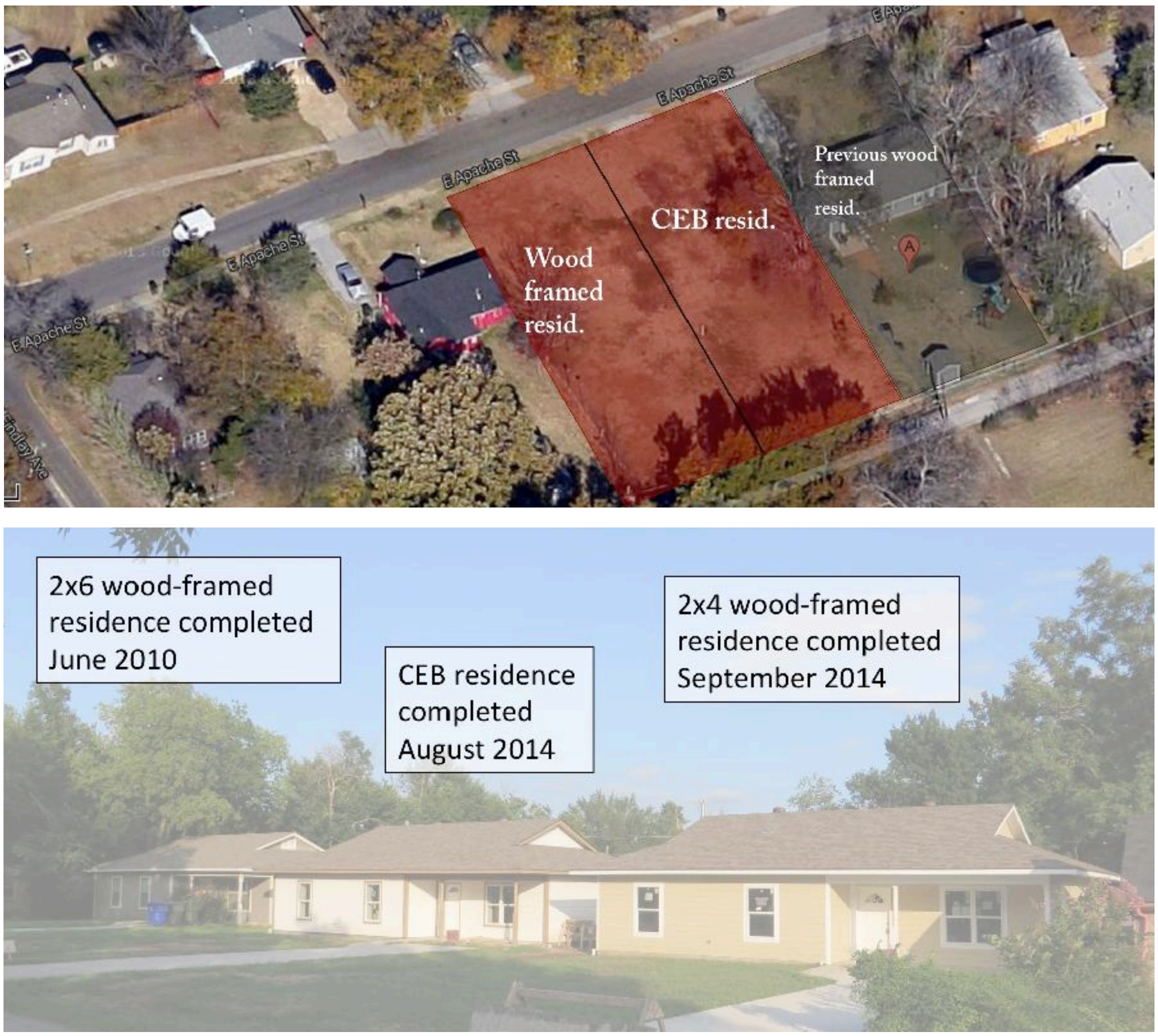


Figure 1: Top photo from Google shows adjacent properties. Bottom photo shows the completed CEB and 2x4 wood-framed residences adjacent to the previously completed 2x6 wood-framed residence in Norman, OK.

Beginning Fall 2010, PI's and Co-PI's Daniel Butko (Architecture), Dr. Lisa Holliday (Construction Science), Matthew Reyes (Construction Science), Scott Williams (Landscape Architecture), and Dean Dr. Charles Graham led the CoA, CoE, and CCHFH collaboration and proposals to both internal and external funding sources. Professors Butko and Holliday developed and co-taught a 22-student multidisciplinary Earthen Design and Construction course in the Fall 2011 semester, leading to the successful completion of the 2012 EPA P3 student competition in Washington D.C. The project was awarded approximately $105k through Phase I and Phase II of the EPA P3 competition, establishing the EPA as the project's main financial research support. Students worked directly with Butko (architect) and Holliday (structural engineer) to produce construction documents for both residences during the Fall 2012 semester, yielding construction permits from the City of Norman, Oklahoma during the Spring 2013 semester. A proof of concept garden/retaining walls, several structural test walls, and a full-scale architectural mockup wall were completed prior to construction. Tests resulted in the selection of a stabilization method (decided from various alternatives to be 7% portland cement by weight) and the use of TenCate Miragrid 3XT® polypropylene geogrid as vertical/lateral reinforcing along interior and exterior faces of CEB walls. Although the team decided to employ Compressed Stabilized Earth Block (CSEB) as the residence walls, the project is typically labeled the CEB residence and simply truncated to CEB. Further laboratory tests will examine the differences between CEB and CSEB as both individual units and composite wall assemblies to determine the acoustical and thermal influence of stabilizers. Potential differences associated with curing times will also be part of the criteria. The team used an AECT 2001A machine to manufacture approximately 8,500 CEB for test walls, mockup walls, and the CCHFH residence.

RESIDENTIAL DESIGN SPECIFICATIONS

Construction of both residences began June 2013 with CEB residence completion August 2014 and wood-framed residence completion September 2014, resulting in certificates of occupancy within CCHFH's typical 16-18 month construction schedule. This article focuses on the acoustical data collected from both residences July 19 and 26, 2014 prior to homeowner occupancy. The acoustical data is a portion of anticipated data collection, including the effect of thermal mass upon comfort and HVAC/energy usage. Thermal and energy consumption measurements are ongoing. Figure 2 defines the interior conditions and some exterior components, while Figure 3 details the exterior wall sections of both residences.

Interior area of entire residences: **1,033 sf**

Interior floor area
- Living Room: **182 sf**
- Living + Kitchen: **369 sf**
- Bedroom: **122 sf**

Surface area of walls, windows, and doors
- Living room wall: **139 sf** including **33 sf** window and **20 sf** door
- Bedroom wall: **95 sf**

Interior cubic volume of entire residences: **8,264 cu. ft.**

Interior cubic volume of living and bedroom
- Living: **1,456 cu. ft.**
- Living + Kitchen: **2,952 cu. ft.**
- Bedroom: **976 cu. ft.**

Steel door w/ steel edge
STC 28, OITC 25
3'-0" x 6'-8"
U-factor: 0.19, SHGC: 0.06

Earthwise E100 Single Hung
(2) 3'-0" x 5'-0"
Vinyl Frame - Double Glaze
LowE + Argon Gas
U-Value: 0.28
SHGC: 0.27
Visible Transmittance: 0.57
Condensation Resistance: 61
STC: approximately 28

Hardiplank STC 40, OITC 28

Figure 2: Interior conditions and component specifications

The mass of the double wythe CEB wall required the use of geogrid cast into the footing below and the bond beam above. The resulting footing and stem wall were much larger compared to the wood-framed residence. This difference also contributes to the acoustical values collected on both wall types.

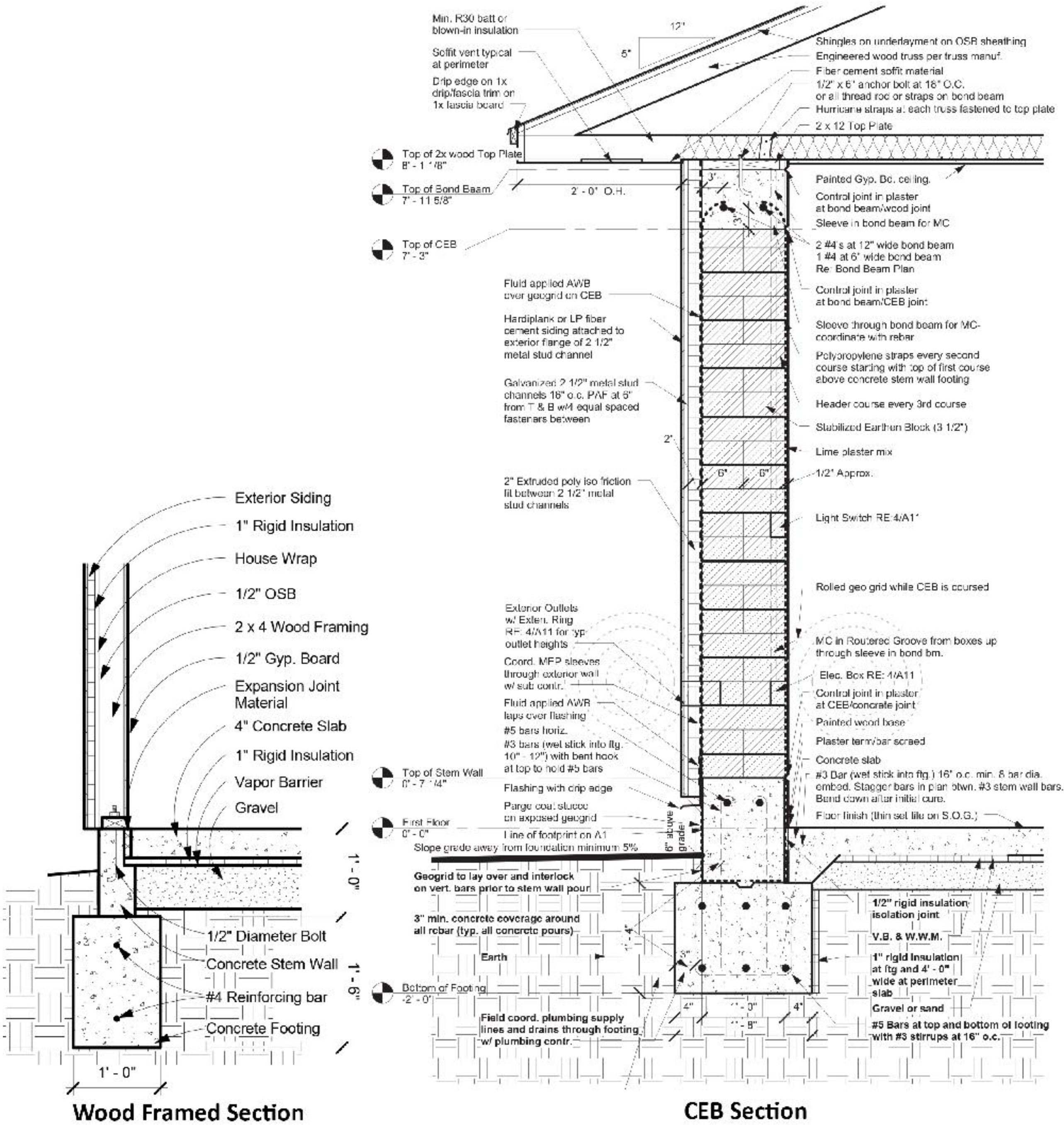


Figure 3: Exterior wall sections of both residences, N.T.S.

As shown in Figure 3, the CEB wall assembly is comprised of HardiePlank® lap siding on 2 ½” 20 gauge metal channels with 2” rigid extruded insulation friction fit between the channels, which are fastened through voids in the geogrid to the exterior wythe of the double wythe CEB wall. The exterior face of the CEB walls were covered with STO® Gold Coat air and weather barrier prior to channel attachment and insulation placement. The interior faces of the CEB walls are covered with American Clay® natural plaster (three coats) totaling approximately ½” thick. The interior plaster keys into both the geogrid and permissible partial head joints in the CEB wall. The exterior geogrid is tied into the courses, and is also held tight with the vertical channels which were fastened to the CEB with masonry anchors into pilot holes or powder actuated fasteners based on field conditions. The entire CEB wall assembly totals 15 ½” – 16” thick from interior to exterior. The wood-framed exterior walls are HardiePlank® lap siding on a sheet air and weather barrier on ½” OSB attached to 2x4 wood studs with R-13 batt insulation in the stud cavities and 1/2" interior gypsum board. The entire wood-framed wall assembly totals 5 ½” thick from interior to exterior. The 5/12 roof is comprised of asphaltic shingles on tar paper on 1/2” (7/16”) OSB on wood trusses with 5/8” gypsum board ceiling (interior) and HardieSoffit® (exterior). The CEB residence trusses are attached to a 2x12 top plate connected by anchors bolts embedded into the concrete bond beam spaced 18” o.c.

ACOUSTICAL FIELD TESTS

The research team worked with CCHFH and adapted acoustical data collection procedures as mandated by the construction and occupancy schedules. Available equipment and time allotted on site also influenced tests performed. The team adhered to ASTM E966-10e1, E1289-08, E1332-10A, E1425-07, E2249-02, E413-04 and industry guidelines as much as possible within the field conditions. Data was collected through a calibrated iSEM EMX-7150 microphone and Studio Six Digital AudioTools app. 94 dBA was verified via a B&K Type 4231 Sound Calibrator prior to measurements. Russ Berger from RBDG Inc. and Daniel Butko provided testing equipment, with all procedures and calibration verified by Jon Birney and Russ Berger (Figure 4).

Figure 4: Jon Birney at RBDG’s office calibrating microphone and AudioTools app prior to site visits

Initial acoustic data was collected July 19, 2014, resulting in established baselines of Noise Criteria (NC) and Noise Isolation Class (NIC). To begin, the microphone was placed 5’-3” above finished floor and 3’–0” from the interior wall surface to measure ambient noise levels in two locations within each residence (defined as living room north wall and bedroom east wall shown in Figures 11 and 12). Data was collected prior to startup of HVAC systems and homeowner occupancy, so ambient background levels defining NC values were based on only typical environmental noise without operable equipment running inside the residences.

The similar NC values (30-32 per Figure 5) were determined to be the result of steady and low environmental noise levels during data collection, without excessive traffic or neighborhood impact. These values can be referenced for future comparisons. Fast Fourier Transform (FFT) and Real Time Analyzer (RTA) values were recorded.

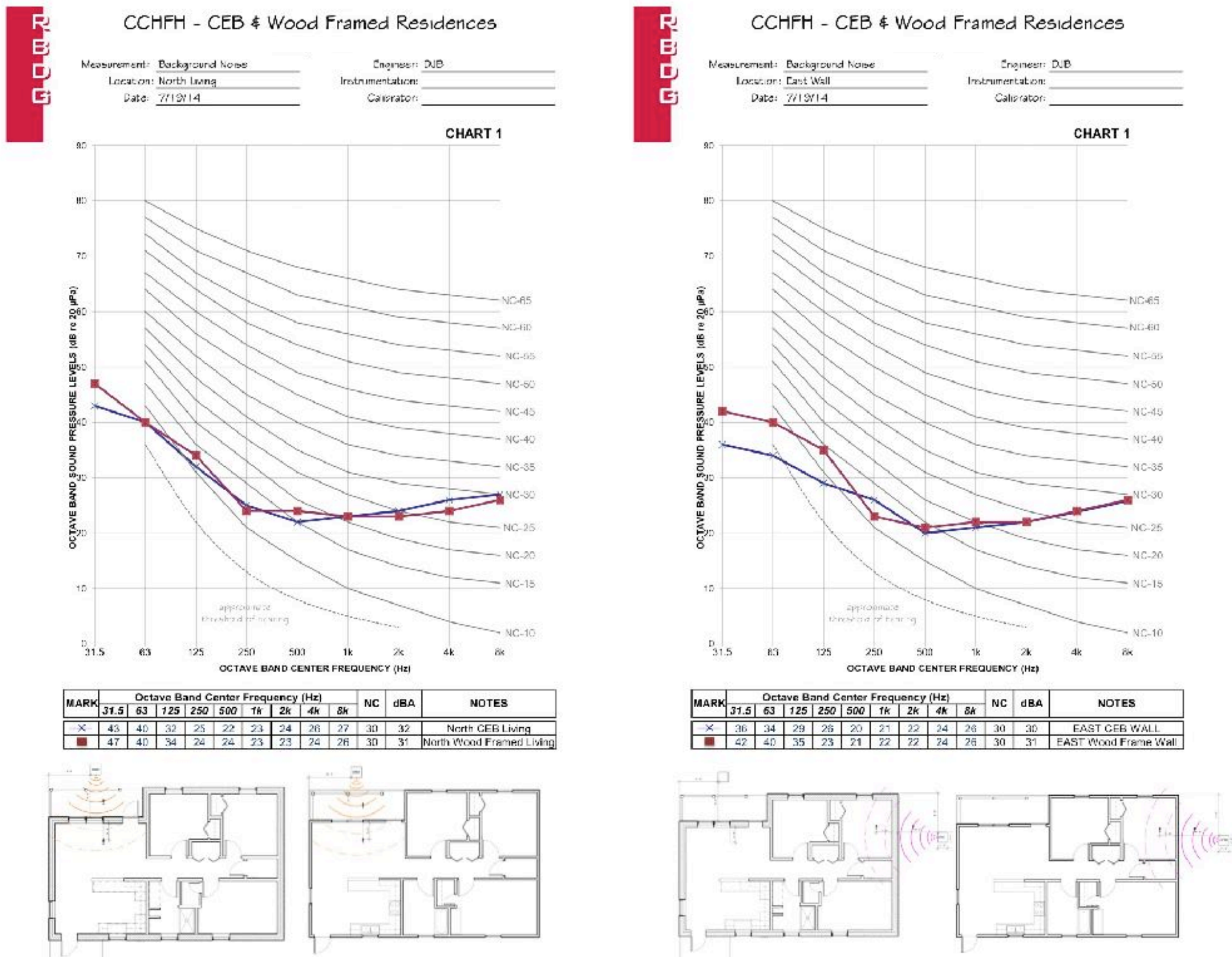


Figure 5: NC charts in presentation slide format from ASA October 2014 meeting

To acquire NIC data, exterior surfaces were bathed in pink noise and resultant energy captured with the microphone located in the same location as the NC data collection. An SWR Bigfoot speaker cabinet housing (2) 12" loudspeakers powered by an Acoustic B200H amp head was connected to an iPad through a Studio Six Digital iAudioInterface2 using a TRS to XLR cable. The interface output allowed the AudioTools app to generate pink noise (Figure 9) to the amp and speaker cabinet, which was manually increased until the AudioTools RTA achieved at least +10 dBA above the ambient background levels per ASTM E966-10e1. Once the interior FFT and RTA values were recorded, the microphone was located 3'-0" from the exterior wall facing the source to define the frequency spectrum and levels of the source.

Pink noise was sent to the speaker cabinet and although both the cabinet and amp were set to flat equalization (EQ), the received spectrum does not reflect pure pink noise (Figure 6). The team believes this is a result of tone coloring from the rig and/or reflections between the two residences. Values are valid for comparison to what is received via the interior data collected.

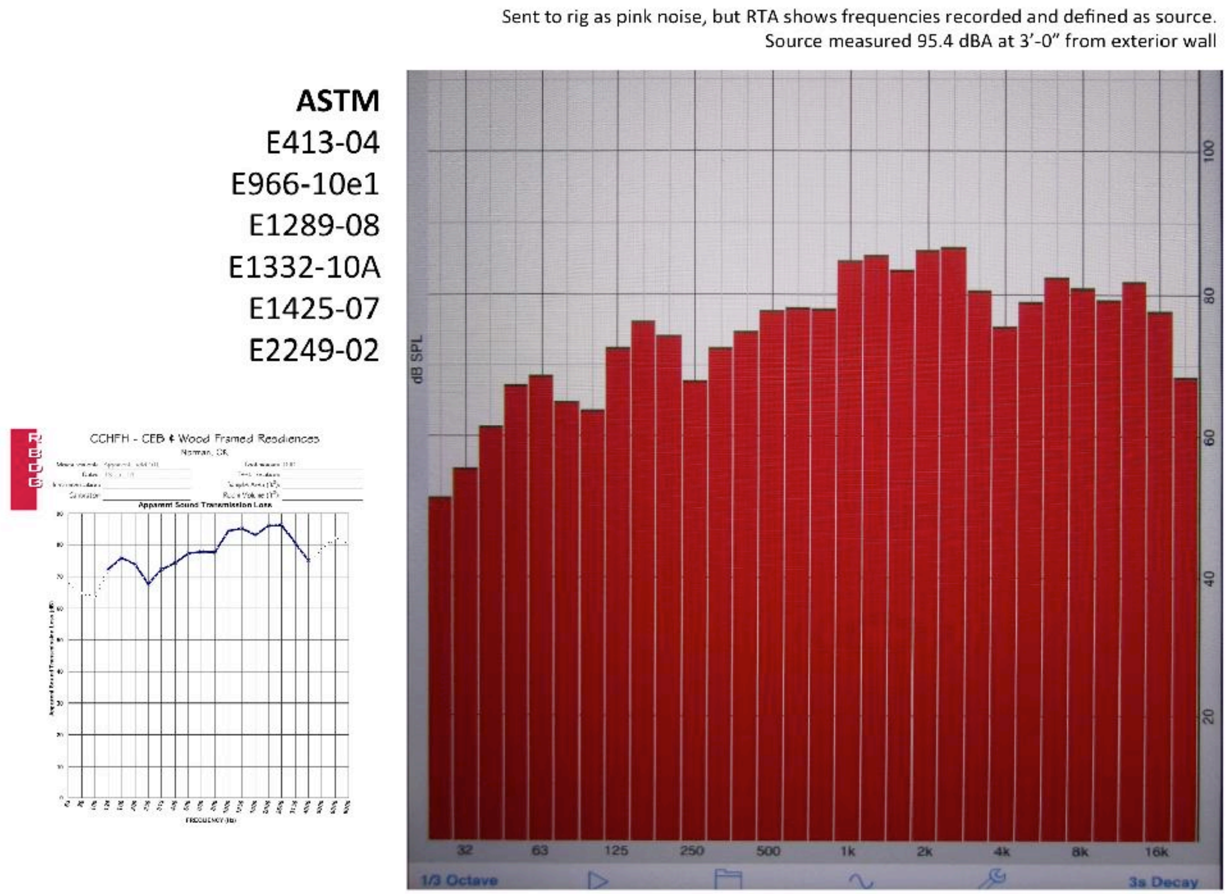


Figure 6: Source frequencies and levels in presentation slide format from ASA October 2014 meeting

The CEB residence east bedroom wall was tested first since it was believed and proved to provide the most isolation. Both residences were subjected to 95.4 dBA pink noise (based upon the minimum +10 dBA above the room NC along the CEB east bedroom wall) per applicable ASTM documents. The continuous CEB east bedroom wall and roof assembly testing yielded +8 dBA (NIC 50) isolation compared to the continuous wood-frame bedroom east bedroom wall and roof assembly (NIC 42). Comparatively, the continuous CEB east bedroom wall and roof assembly test yielded +17 dB (NIC 50) isolation compared to the CEB north living room wall and roof assembly (NIC 33), which included fenestrations (door and operable windows) shown in Figure 7 with resultant NIC values defined in Figure 8. At first the NIC values may appear lower than expected, but the team believes they are accurate/valid since they account for fenestrations and the roof assembly.

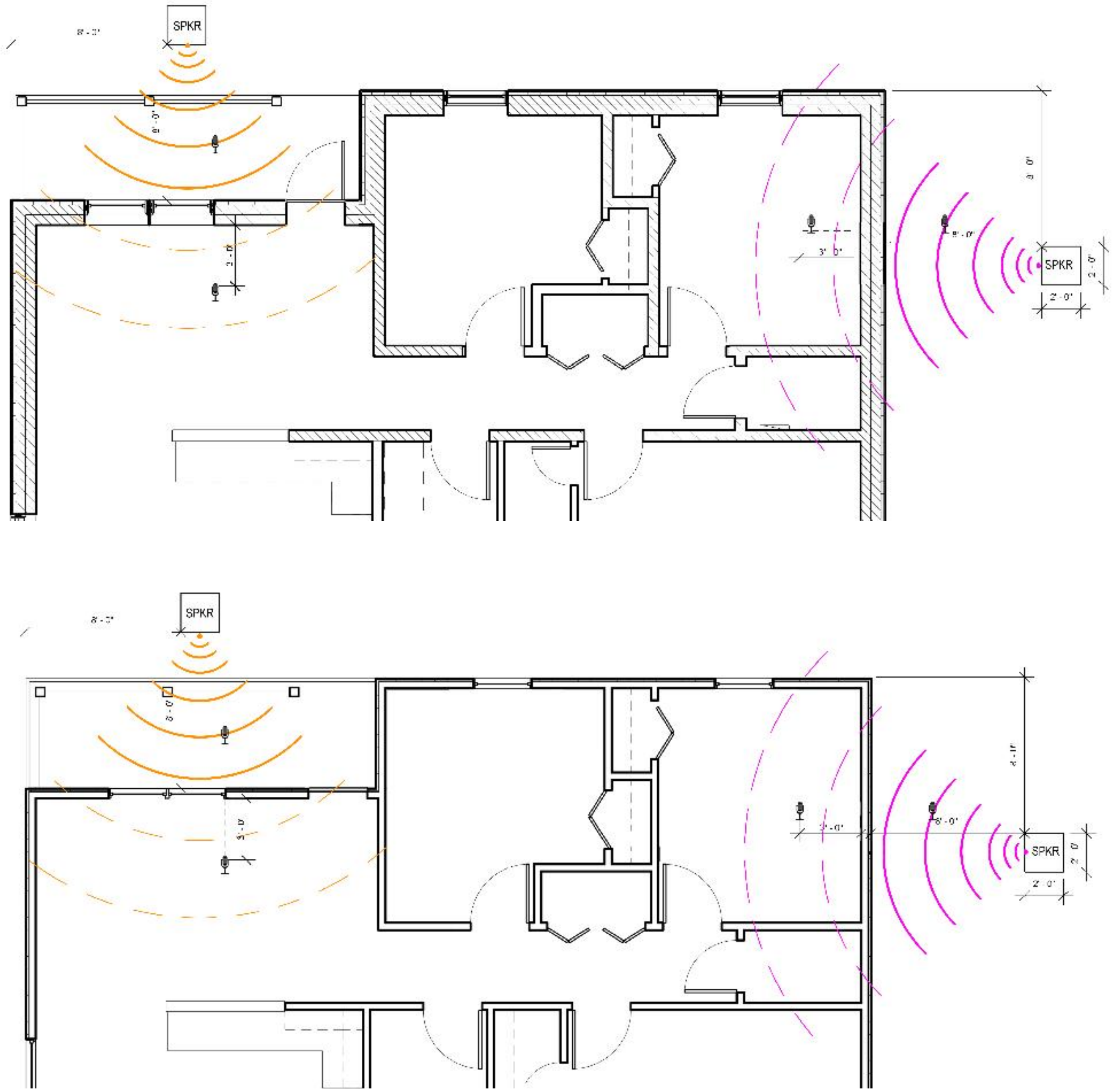
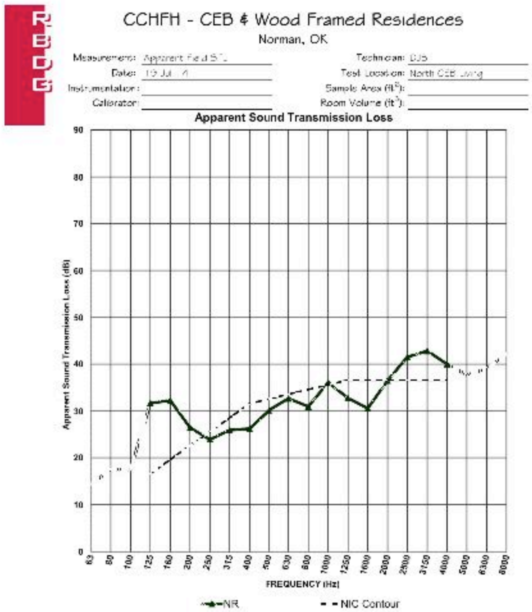


Figure 7: Partial plans of both residences depicting acoustical source and receiver locations. CEB residence (top), Wood-framed residence (bottom). North is upward on the page. N.T.S.

Due to the 10’-0” side yard between residences and the SWR cabinet being 18” deep, the front of the cabinet was located 8’-0” from the wall surface to allow rear cable connections as shown in Figures 7 and 10. The 8’-0” distance was duplicated at the remaining three test locations. Temperatures and relative humidity levels were noticeably different in both residences (CEB residence felt cooler and presumably has a lower relative humidity due to the thermal mass and wall density), but not considered varied enough to affect test results or comparative values. The following images (Figures 8-14) depict the process of collecting data July 19 and July 26, 2014 with additional descriptions throughout concluding paragraphs.

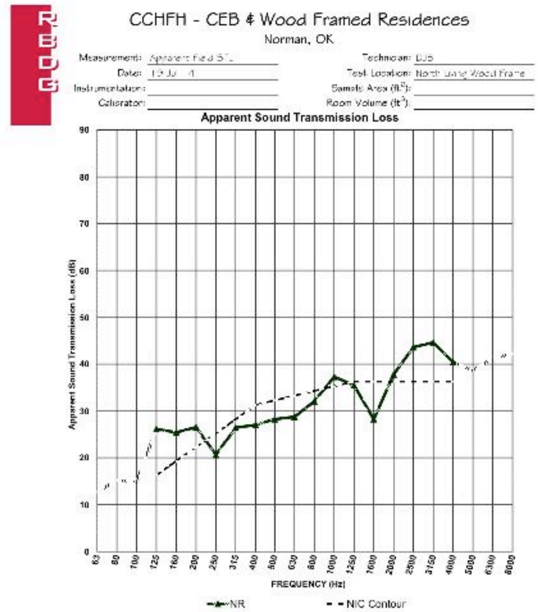


NIC 33

MARK	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000
✕	72	76	74	68	72	74	77	78	78	84	85	83	86	86	80	75
●	41	44	47	44	46	48	47	45	47	48	52	53	50	45	38	35
▲	32	32	27	24	26	26	30	33	31	36	33	31	37	42	43	40

(Third Octave Band Frequency (Hz))

CEB residence
Living Room
Source at north wall

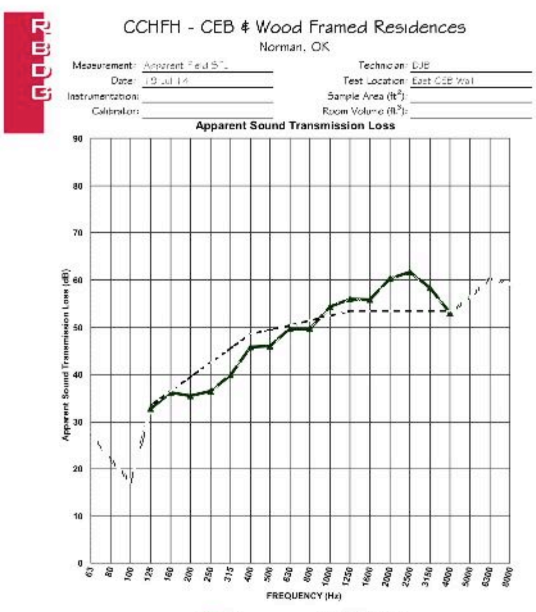


NIC 32

MARK	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000
✕	72	76	74	68	72	74	77	78	78	84	85	83	86	86	80	75
●	46	50	47	47	46	47	49	49	46	47	50	55	48	43	36	35
▲	26	26	27	21	27	27	28	29	32	37	36	28	38	44	45	40

(Third Octave Band Frequency (Hz))

Wood-framed
residence
Living Room
Source at north wall

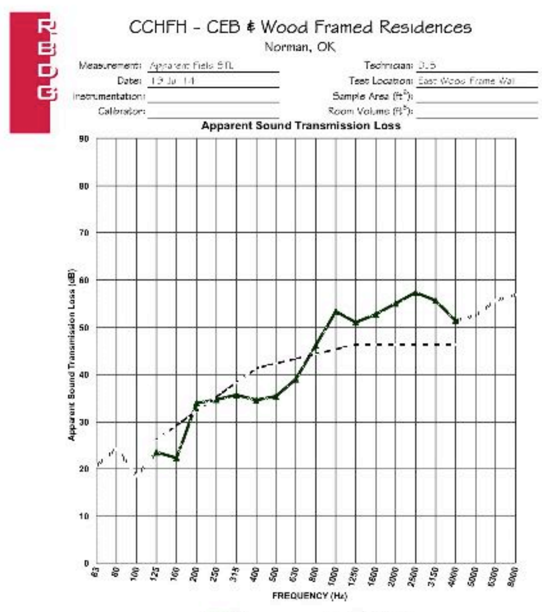


NIC 50

MARK	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000
✕	72	76	74	68	72	74	77	78	78	84	85	83	86	86	80	75
●	40	40	38	31	32	29	31	28	28	30	29	27	26	25	22	22
▲	33	36	36	37	40	46	46	50	50	54	56	56	60	62	58	53

(Third Octave Band Frequency (Hz))

CEB residence
East Bedroom



NIC 42

MARK	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000
✕	72	76	74	68	72	74	77	78	78	84	85	83	86	86	80	75
●	49	54	40	33	37	40	42	39	32	31	34	30	31	29	25	24
▲	24	22	34	35	36	35	35	39	46	53	51	53	55	57	56	52

(Third Octave Band Frequency (Hz))

Wood-framed
residence
East Bedroom

Figure 8: NIC values at all four locations in presentation slide format from ASA October 2014 meeting

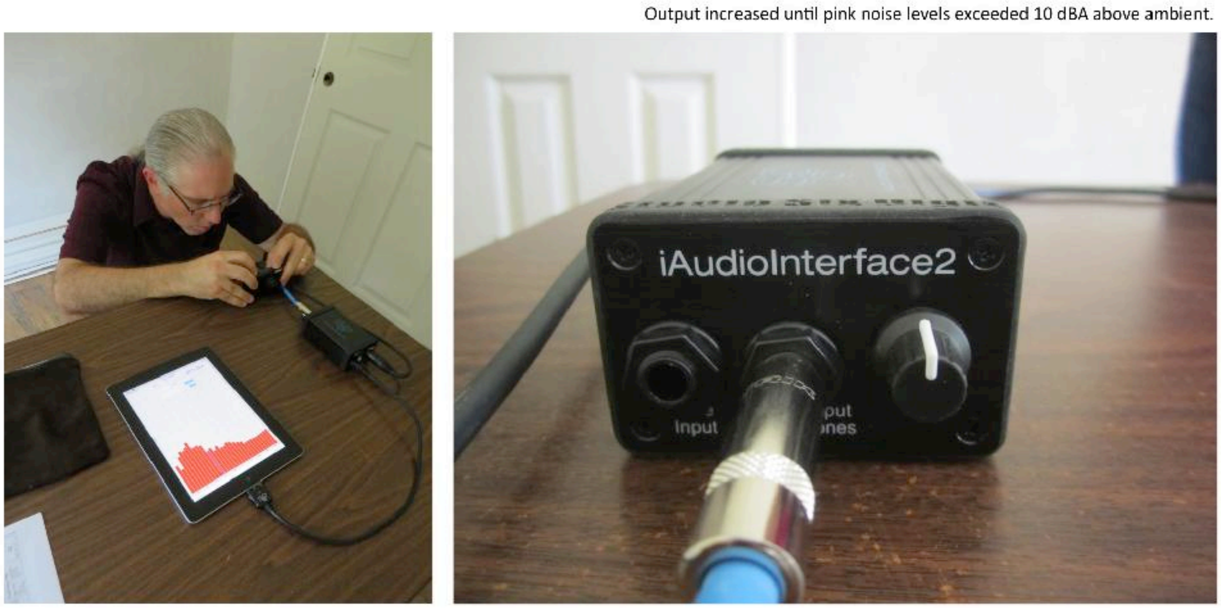


Figure 9: Images depict interface, iPad, and Studio Six Digital software

Figure 10: Images depict bathing exterior walls/elevations with pink noise in presentation slide format from ASA October 2014 meeting

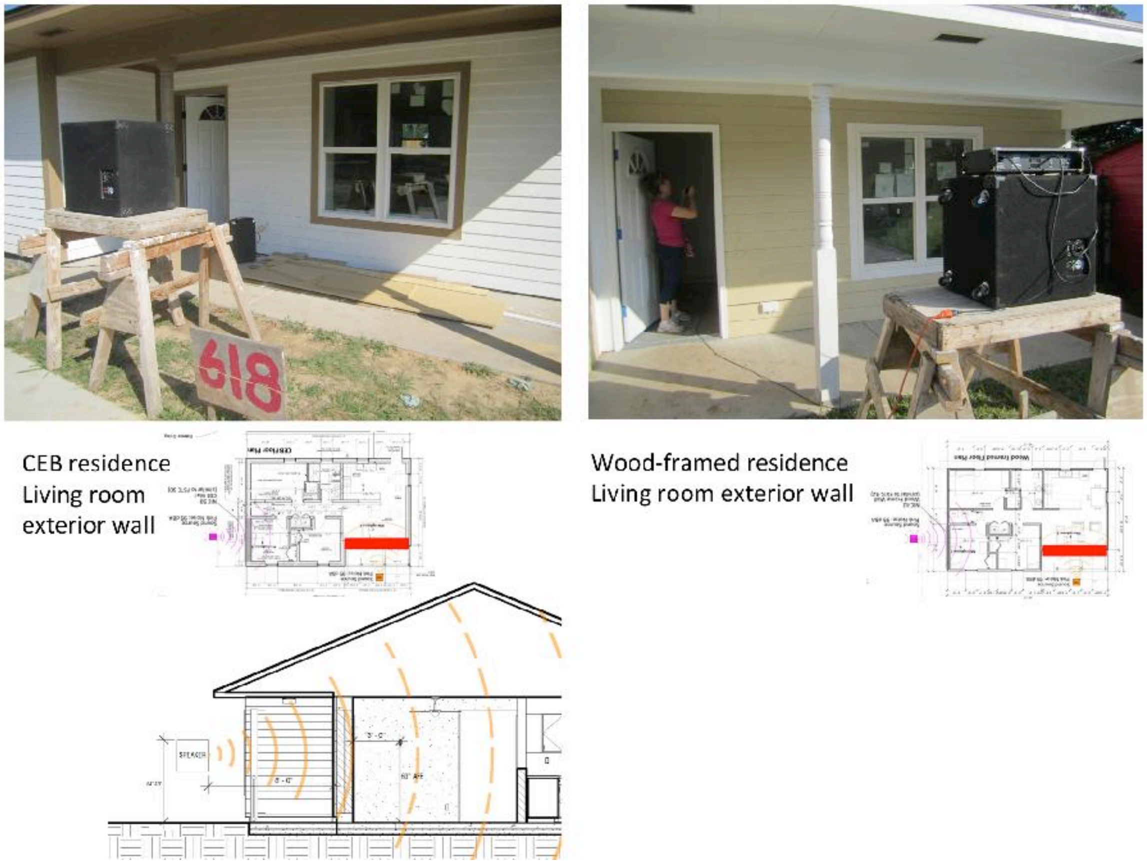


Figure 11: Images depict setting up sound source for north living room wall data collection in presentation slide format from ASA October 2014 meeting

Figure 12: Recording NC and NIC values in presentation slide format from ASA October 2014 meeting. Images depict microphone placement of 5'-3" AFF and 3'-0" from interior surface.

Portions of the tests were repeated July 26, 2014 to verify accuracy, concluding with parallel values. Temperatures and relative humidity levels were also consistent and similar to those observed July 19, 2014. A series of additional tests were completed to determine if sound entry through the north bedroom window, electrical outlets, HVAC supply air diffuser, and/or attic access panel contributed to interior receiver values. Figures 13 and 14 depict the dBA receiver values and testing locations in the wood-frame residence.

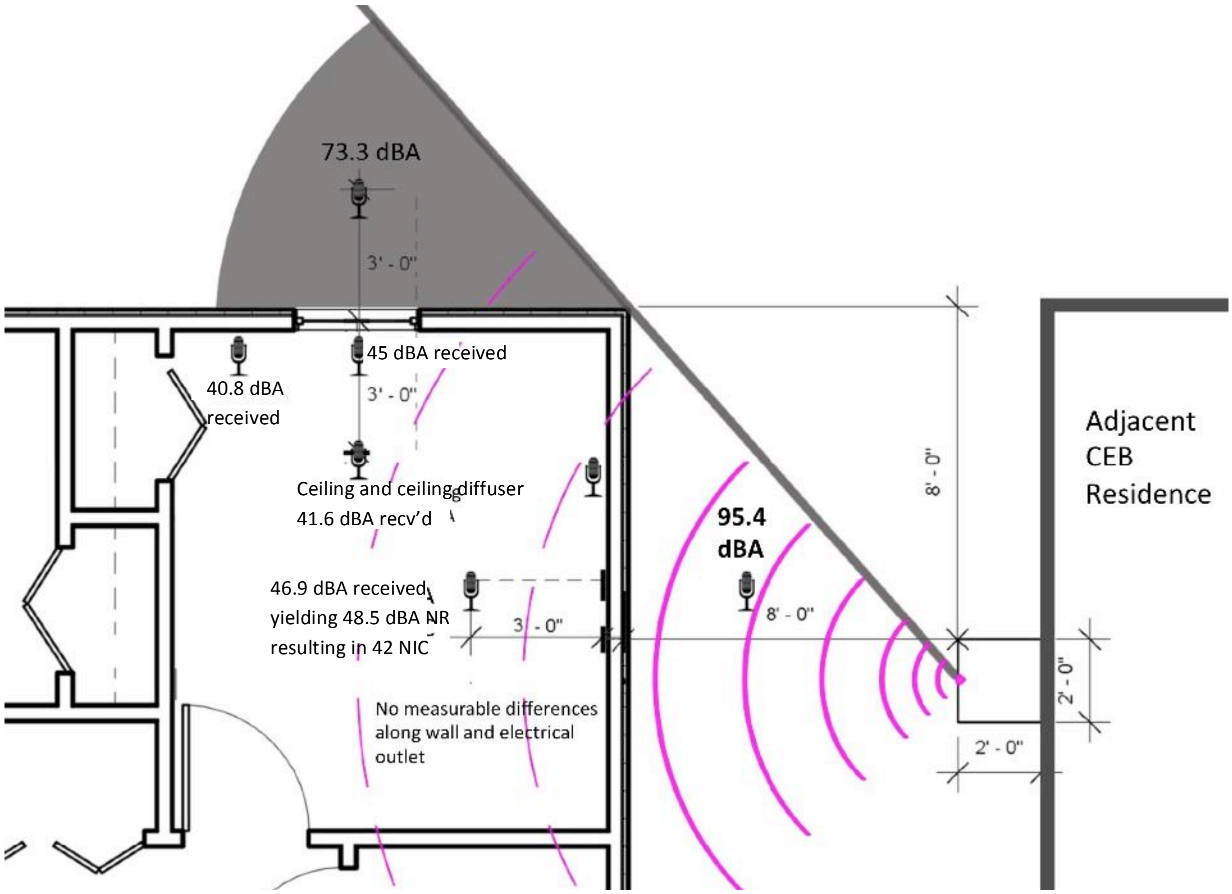


Figure 13: Partial plan depicts 22.1 dBA decrease around corner and diminishing values at/near window

The fenestration in question along the north face is around an outside corner from the sound source on the east side of the residence. Figure 13 depicts the 22.1 dBA decrease within the acoustical shadow and decreased interior values. Based upon the data collected, the team determined the aforementioned flanking paths did not influence the previously collected values for both east walls. Overall, fenestrations and the roof assembly are flanking sound paths dependent upon location of the receiver, resulting in values lower than a completely isolated CEB wall. The team concluded only the roof assembly was a factor when collecting data along the east wall while the front door, windows, and roof assembly (same construction and connections as the roof assembly noted at the CEB east bedroom wall) in the living room were direct flanking paths causing lower NIC values. The initial NIC values of 50 (CEB wall) and 42 (wood-framed wall) were supported. Figure 15 (complemented by Figure 16) shows the relationship between the two solid wall/roof NIC values. Additional data is defined in the Appendix depicting all differences between all frequencies collected.

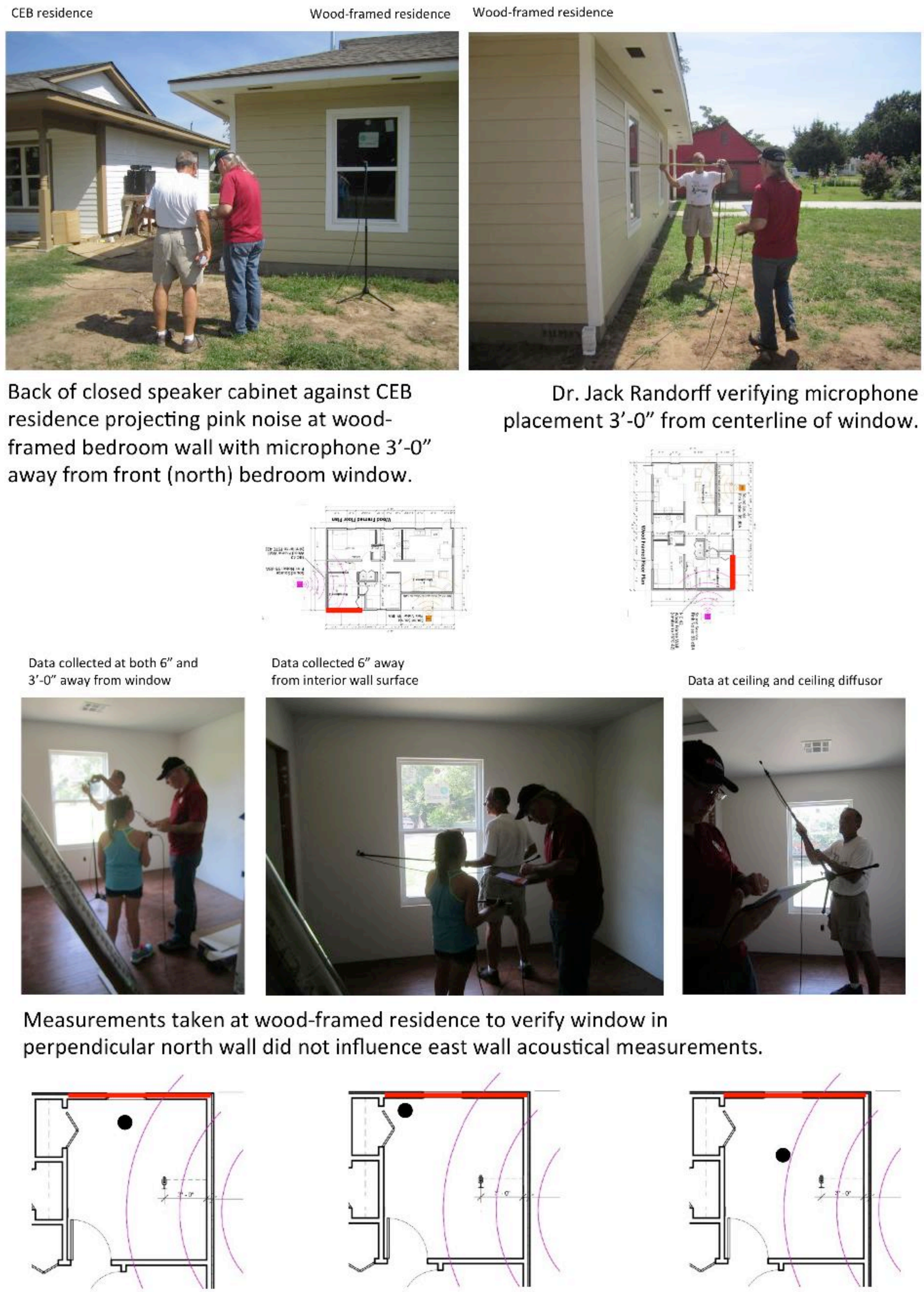


Figure 14: Series of images and photographs (in presentation slide format from ASA October 2014 meeting) depict additional tests to determine if flanking path of north bedroom window adversely affected previously recorded wall NIC values

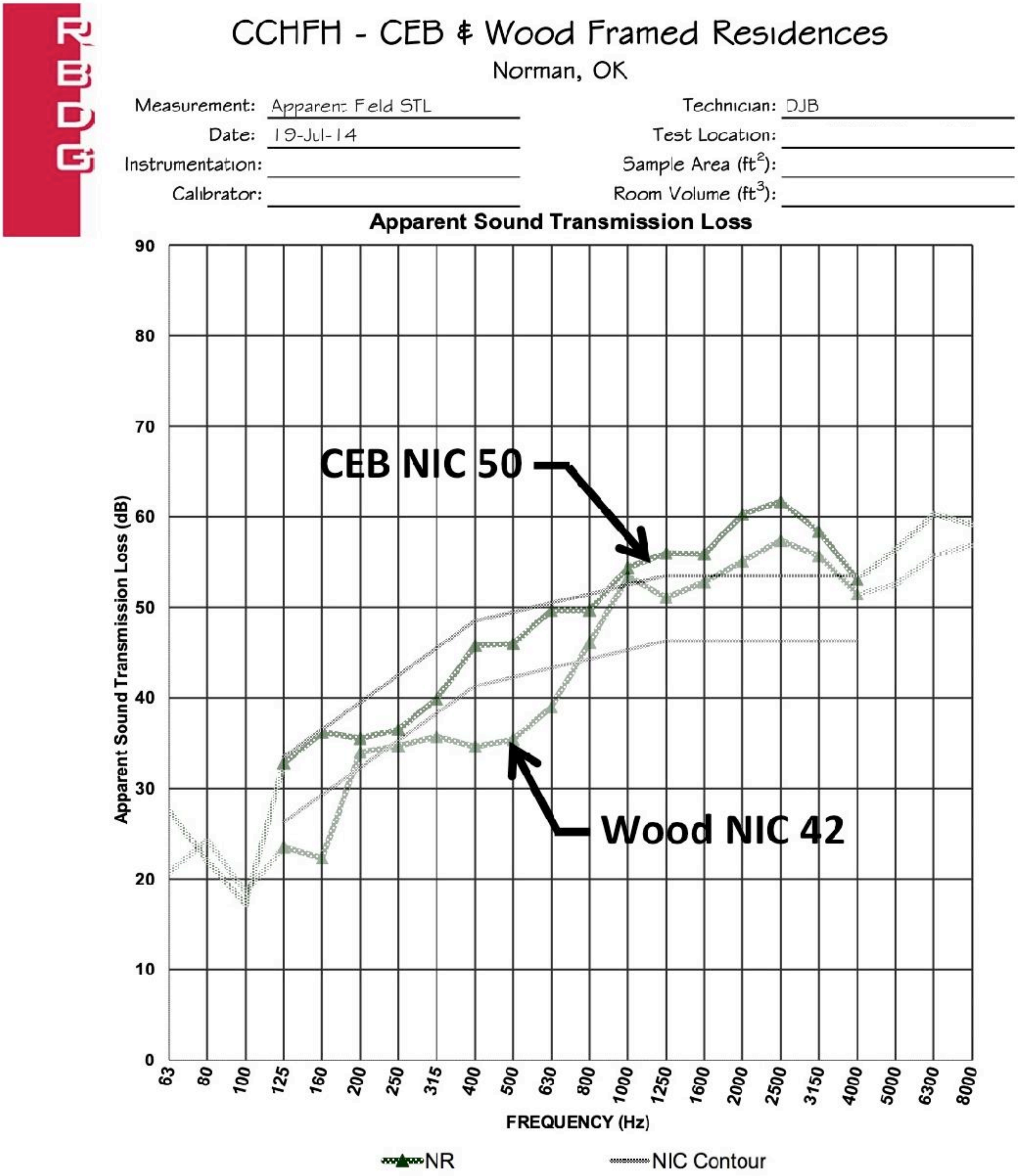
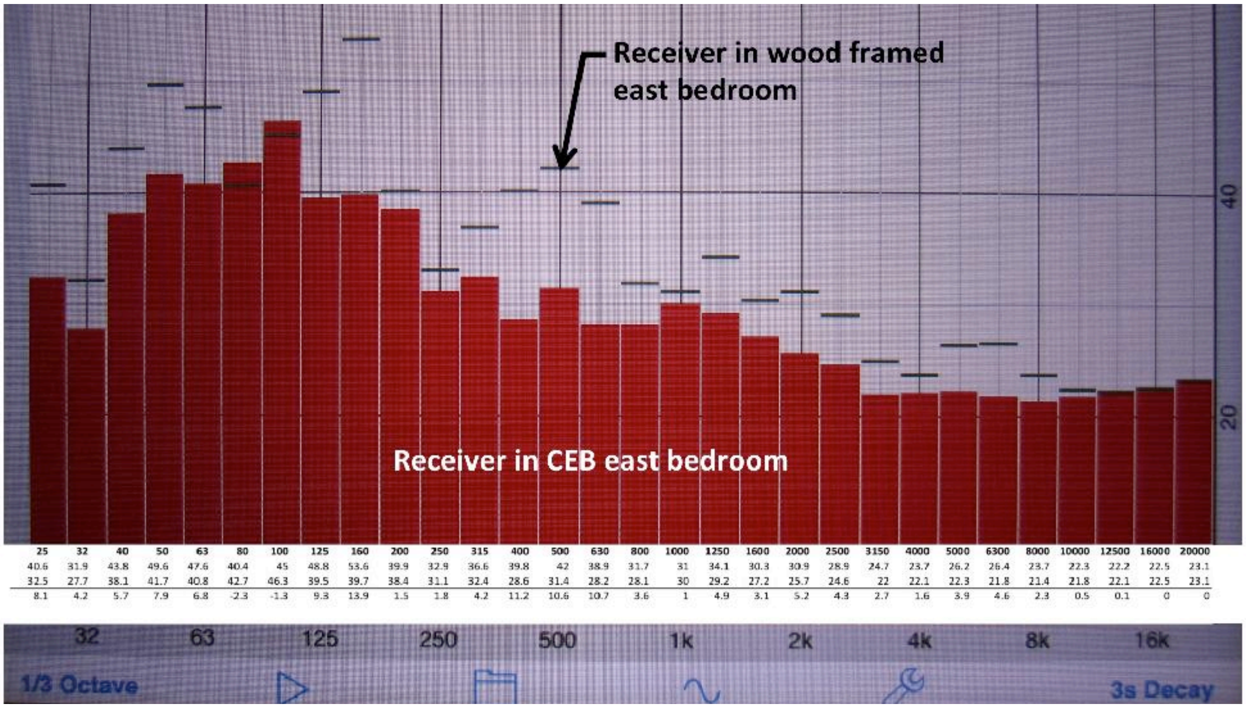


Figure 15: Comparing CEB and wood-framed NIC values



25	32	40	50	63	80	100	125	160	200	250	315	400	500	630	800
40.6	31.9	43.8	49.6	47.6	40.4	45	48.8	53.6	39.9	32.9	36.6	39.8	42	38.9	31.7
32.5	27.7	38.1	41.7	40.8	42.7	46.3	39.5	39.7	38.4	31.1	32.4	28.6	31.4	28.2	28.1
8.1	4.2	5.7	7.9	6.8	-2.3	-1.3	9.3	13.9	1.5	1.8	4.2	11.2	10.6	10.7	3.6

1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000	12500	16000	20000
31	34.1	30.3	30.9	28.9	24.7	23.7	26.2	26.4	23.7	22.3	22.2	22.5	23.1
30	29.2	27.2	25.7	24.6	22	22.1	22.3	21.8	21.4	21.8	22.1	22.5	23.1
1	4.9	3.1	5.2	4.3	2.7	1.6	3.9	4.6	2.3	0.5	0.1	0	0

Figure 16: Image depicts differences in frequency spectrum between CEB and wood-framed east bedroom wall.

ADDITIONAL TEACHING TOOLS

Upon completion of the NIC data collection, four Shure SM57 microphones were placed in four locations in the CEB residence followed by the wood-framed residence per Figure 17. Each microphone was connected to a digital multi-track recorder for 4-track simultaneous recording. A series of claps were recorded to document the reverberant character and overall acoustical ambiance of each residence. Listening through headphones informs listeners of the acoustical differences between the two residences, especially the ring modulation within the wood-framed house due to the singularity of gypsum board faced walls and partitions compared to the primary plaster surfaces keyed through the geogrid and into dense earth blocks.

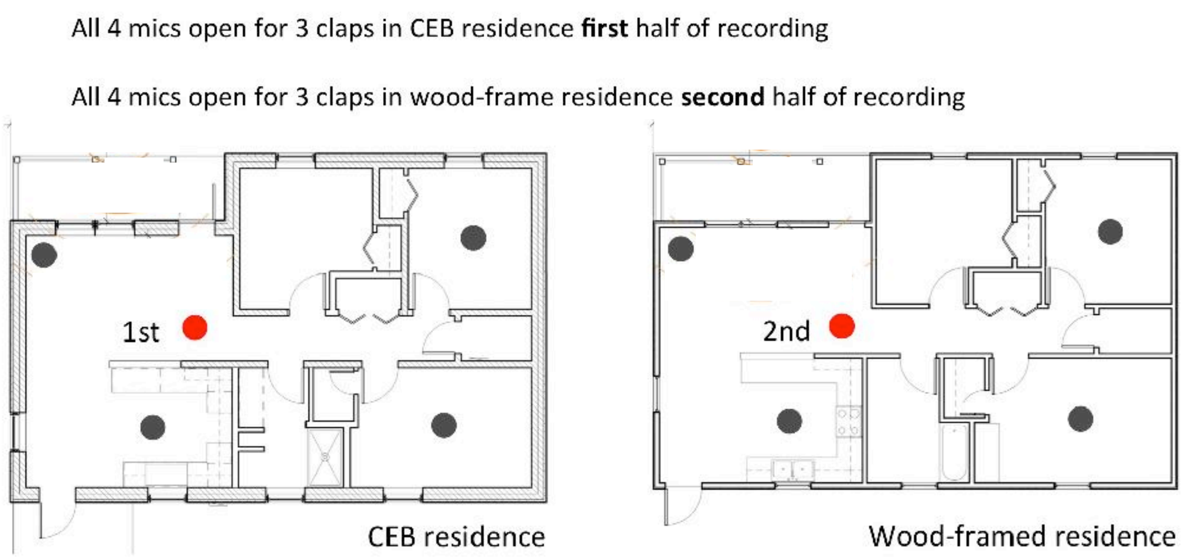


Figure 17: Locations of microphones for multi-track recording shown in black. Location of source clapping shown in red. Images shown in presentation slide format from ASA October 2014 meeting.

Additional multi-track recordings were made to document the exterior source in relation to received locations within each residence. Figure 18 depicts locations of recordings at exterior source with all four interior locations mixed equally for an overall stereo signal or the option of each channel being isolated for individual playback. Five tracks were used to capture the source and four locations independently. Figure 19 depicts the relationship between exterior source and each bedroom as a separate presentation for comparison. Listeners can then aurally connect the source, the reverberant qualities of the spaces, and the received values for both residences. The recordings were presented during the October 2014 ASA presentation and can be made available upon request.

Aside from the collected data, there is also an acoustical comfort level difference between the two residences. The acoustical nature of the CEB residence is pleasant to the ears due to more of the source frequencies reflecting back into the space. The deep window recesses, softened corners, and the texture of the CEB residence plaster contribute to more broadband frequency reflections. The 0.1 NRC value of the interior American Clay® plaster is enhanced through keying tightly into the 12" thick dense CEB and geogrid. The compound density provides strong lateral acoustical reflections to the interior spaces resulting in less sound energy being lost into or absorbed through the wall assemblies. The reflections define particular acoustical warmth to the spaces since more of the low frequency energy is reflected back into the interior spaces. The increased reflections in the CEB residence promote lower source amplitude for interior sound sources to seem similar to louder sources inside the wood-framed residence. Students and visitors immediately notice the difference in comfort (both thermal and acoustical) upon entering the residences.

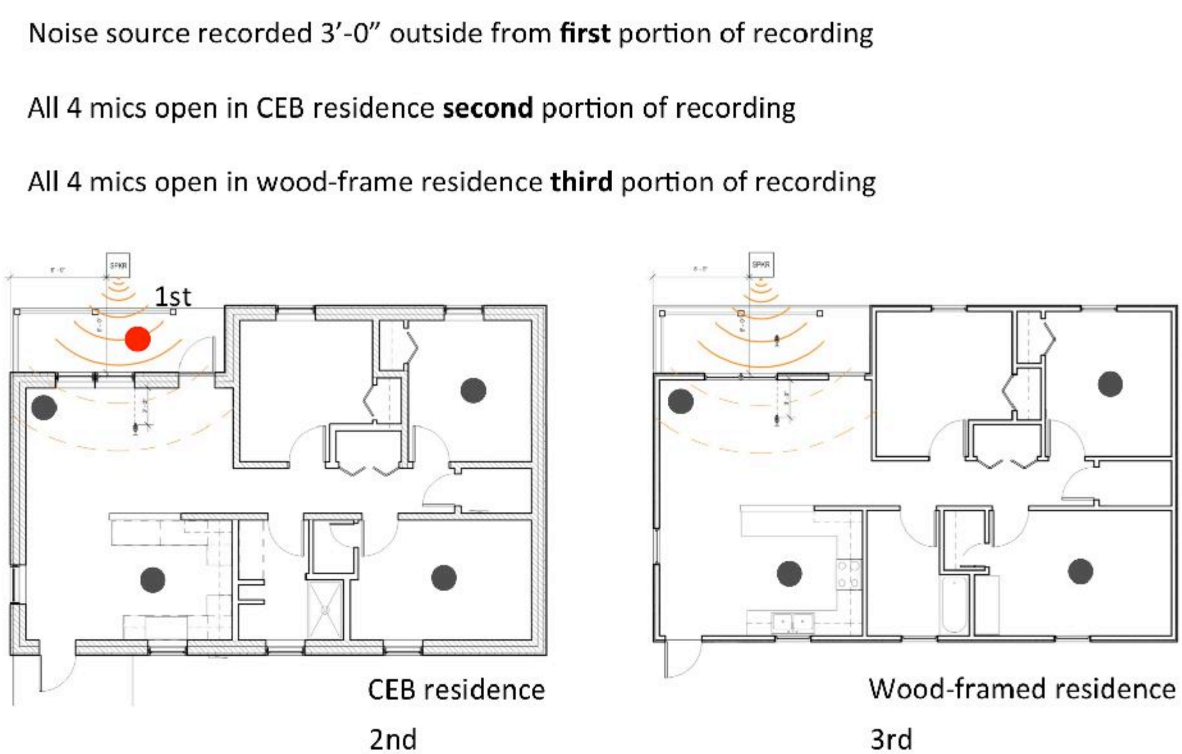


Figure 18: Images depict process of comparing exterior sound source to receiver of four microphones recorded on separate channels mixed equally. Data collected informs students of composite noise reduction based on entire residence. Images shown in presentation slide format from ASA October 2014 meeting.

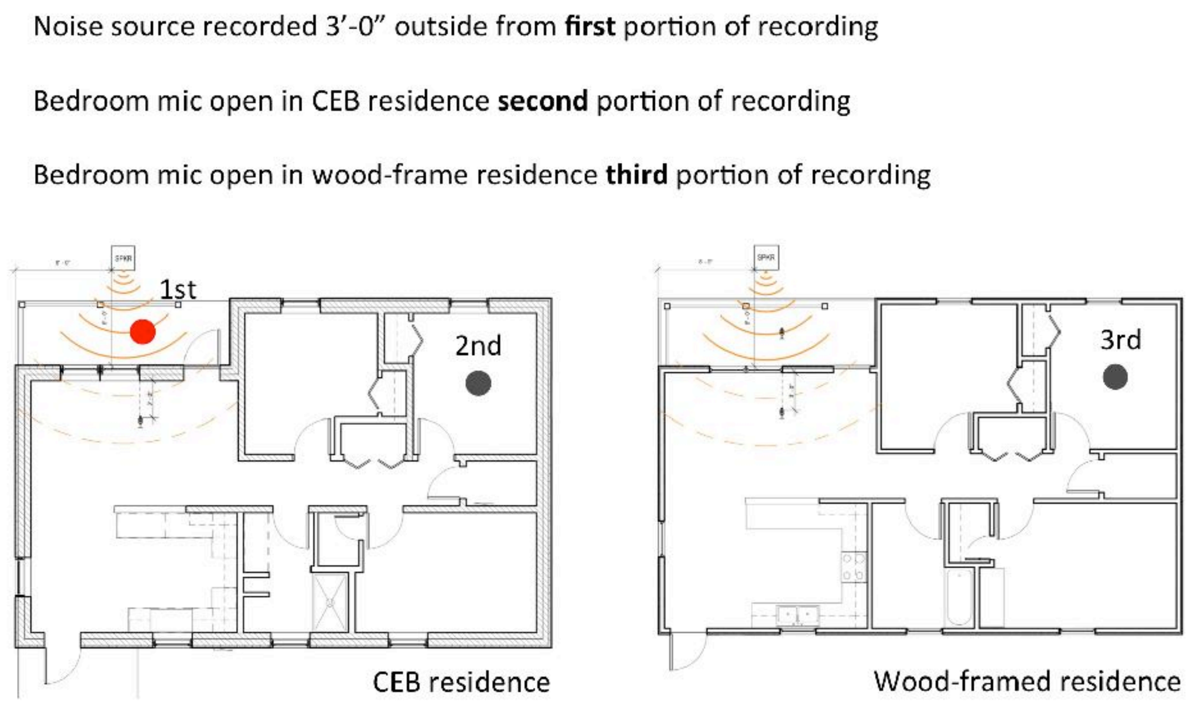


Figure 19: Images depict comparisons of exterior sound source at north living room walls to recorded receivers in east bedrooms of both residences. Data collected informs students of composite noise reduction based on entire residence. Images shown in presentation slide format from ASA October 2014 meeting.

SUMMARY

The team believes the results of the completed acoustical data collection are informative and help inform researchers, developers, clients, and students about the acoustical benefits to CEB (stabilized or non-stabilized) construction. The team explains the 8 dBA difference between the CEB wall and the wood-framed wall as significant based upon the rule-of-thumb where every 10 dBA relates to a doubling or halving the comparatively measured sound source. The NIC field-tests provided data to support the initial belief the CEB walls would provide more isolation between interior and exterior sources. The CEB wall provided almost twice the sound loss when compared to the wood-framed wall, without compromising the necessary audible alert of storm warning sirens which still arrive to interior spaces through the roof assembly, doors, and windows. The team will continue the acoustical data collection through a relationship with a recognized acoustical testing laboratory. The laboratory data will complement the field data to ultimately provide Sound Transmission Class (STC) and Transmission Loss (TL) values for publication in comparison to the collected 50 and 42 NIC values. Continued research and future publications could include relation to rammed earth, adobe, cob, and other alternative or earthen building materials.

APPENDIX:

- SWR Bigfoot speaker cabinet housing (2) 12” loudspeakers at 45 degree diagonal placement
- Powered by an Acoustic B200H amp head
- Flat EQ
- iPad connected to the iAudioInterface2
- Pink noise from the iPad sent via TRS cable through interface output to the loudspeaker rig, subjecting all four walls to equal levels of noise.
- Interface output until the RTA achieved a minimum +10 dBA above the ambient background levels per ASTM E966
- CEB east bedroom wall tested first to determine source noise level to overcome wall density.
- The HVAC systems were not operational at the time of data collection, so the ambient background levels defining the NC values were based on only typical environmental noise without operable equipment running inside residences.
- iSEM EMX-7150 microphone placed 63” above finished floor and a 3’–0” from the wall surface facing the wall surface on the interior and 3’-0” from the exterior wall facing the SWR cabinet. Top of cabinet 64” above grade, bottom 44” above grade.
- The Studio Six Digital software calibrated using a B&K Type 4231 Sound Calibrator while the mic was connected. 94 dB was verified.

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