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Assessment of Building Retrofit Options Using Hygrothermal Analysis Tool

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SUMMARY

As the stock of buildings in our society ages, it is expected that there will be an increase in building envelope rehabilitation work. Such activities represent an ideal opportunity to modify the existing wall system to improve building envelope durability and energy efficiency. This could be done by addition of insulation and sealing air leakage paths. However, there is very little information available on how to assess the moisture and energy (i.e. thermal) performance of retrofitted building envelope assemblies and select the optimum retrofit options that will maximize the long-term moisture performance and the energy efficiency of the retrofitted building envelopes together. This paper presents the findings from a study that has used a two-dimensional hygrothermal simulation tool, *hygIRC-2D*, to assess moisture and energy performance of retrofitted masonry walls used in high-rise construction for both residential and commercial types of buildings at various Canadian locations. The results from the simulations indicate that, if heat, air and moisture transport properties of the materials and the airflow characteristics of the systems can be defined properly a hygrothermal simulation tool can be used to evaluate the moisture and thermal (i.e. energy) performance of various wall systems and associated retrofit options.

KEYWORDS
Retrofit, Building Envelope, Hygrothermal Simulation

INTRODUCTION

Building envelopes age and in due course they may require rehabilitation or retrofit to maintain effective serviceability. At the same time, building construction technology and the materials used for construction change over the years. The chance to retrofit a building envelope offers a great opportunity to upgrade it for thermal (i.e. energy) and moisture performance. This can be done by adding insulation, reducing air leakage, and improving the moisture control strategies that will enhance occupant comfort and durability of the building envelope. However, to assess the extent to which this can be done and determine the best available methods to adopt are challenging tasks for building envelope designers. There is no comprehensive methodology, for combined energy and moisture performance assessment, available that can be used for this purpose. Currently, the Institute for Research in Construction (IRC)/National Research Council (NRC) of Canada, in association with a number of Canadian government agencies, has embarked on a research program to address this concern. The main purpose of this research project is to develop a knowledge base about the moisture and thermal performance of retrofitted high-rise wall assemblies using advanced hygrothermal simulation tools and well-defined reliable material properties. The simulation outputs obtained from this study have been critically analysed using appropriate energy and moisture performance indicators. An outline of the various steps and tools used in the analysis process and overall outcomes from the study are presented in the following paragraphs.

RESEARCH OBJECTIVE AND SCOPE

The primary aim of this paper is to demonstrate that hygrothermal simulation tools can be used to identify the appropriate retrofit options for a typical Brick Veneer - Steel Stud (BV/SS) wall assemblies commonly found in high-rise residential (Wall height 2.5 m) constructions at five geographic locations: Halifax (Shearwater), National Capital Region (Ottawa-Hull), Toronto, Winnipeg, Vancouver.
Similar analyses were done also for Brick Veneer - Concrete Masonry Unit (BV/CMU), Precast Concrete Panels - Steel Stud Unit (CV/SS), Thin Stone Veneer-Concrete Masonry Unit (SV/CMU) and Stone Veneer

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- Load Bearing Brick Masonry (SV/BMU) walls. However, due to limitation of space only the selected results from the Brick Veneer - Steel Stud (BV/SS) wall will be discussed in this paper.

HEAT, AIR AND MOISTURE PERFORMANCE ANALYSIS USING *hygIRC-2D*

IRC's advanced two-dimensional hygrothermal modeling tool *hygIRC-2D* was used to assess the hygrothermal conditions in the envelope components of the various assemblies. *Karagiozis, 1993, 1997, and Djebbar, 2002* outline the formulation of the combined heat, air and moisture transport equations used in *hygIRC-2D* and the techniques used to numerically solve them. The validity of *hygIRC-2D* outputs has been established through laboratory measurements and benchmarking exercises (*Maref et al. 2002 and Hagentoft et al. 2003*). Various input parameters involved in this study are described in the following paragraphs.

Base Case Wall Construction
The construction details of base case Brick Veneer - Steel Stud (BV/SS) wall assembly and various retrofit options considered in this study are shown in Figure 1.

Various Retrofit Options
Four retrofit options are Interior Retrofit I, Interior Retrofit II, Interior - Exterior Retrofit, and Air Sealing Retrofit, as shown in Figure 2. All four retrofit options were designed to increase the air-tightness of the wall system by 40% (i.e. from 2.5 L/s.m^2 to 1.5 L/s.m^2 @ 75 Pa). The air-tightness of the wall was increased by controlling the airflow or air-leakage characteristics of the wall assembly.

Simulation Duration
The simulations were carried out over a period of three years (1095 days/26280 hours). One initiation weather year was followed by two critical weather year conditions, selected on the basis of wind-driven rain on the exterior wall.

Material Properties
Simulation using *hygIRC-2D* requires eight sets of material properties: air permeability, thermal conductivity, dry density, heat capacity, sorption characteristics, suction pressure, liquid diffusivity, and water vapour permeability. These properties were taken from the IRC's material properties database generated at the Thermal and Moisture Performance Laboratory of the institute.

Boundary Conditions
The interior boundary conditions for all geographic locations were generated in such a way that correctly reflects the field conditions (*Djebbar et al. 2003*). Typical plots of interior boundary conditions at Halifax (Shearwater) are shown in Figure 3.

SIMULATION OUTPUTS AND ANALYSIS OF THE RESULTS

A significant amount of data were generated from 25 simulations, presented in this paper, and subsequently post-processed for the detailed energy and moisture performance evaluation of the simulated wall assemblies. Comprehensive details of the analysis method were documented in the reports authored by *Djebbar et al. (2002a), Nofal and Tariku (2002)* and *Mukhopadhyaya et al. (2005).*
The moisture response of the wall systems were assessed in terms of RHTT index and Freeze-thaw (FT) index, the energy efficiency of the wall systems were determined from the values of yearly heat balance across the envelope and the long-term performance were assessed in terms of biological activity (i.e. mold growth). The basic definitions of these evaluation indices or parameters have been already presented elsewhere (*Djebbar et al. 2002b, Djebbar et al. 2002a and Nofal and Tariku 2002*). However, for the readers' convenience, the definitions of these evaluation indices or parameters are again described in the following paragraphs.

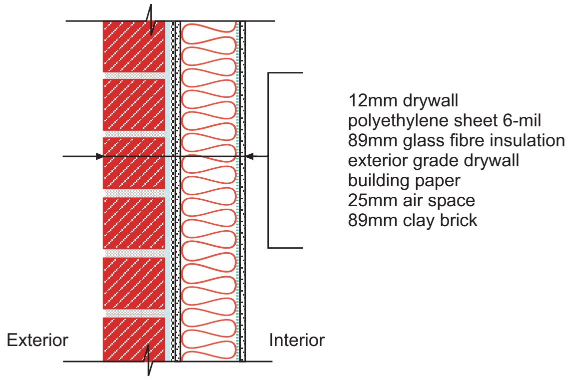
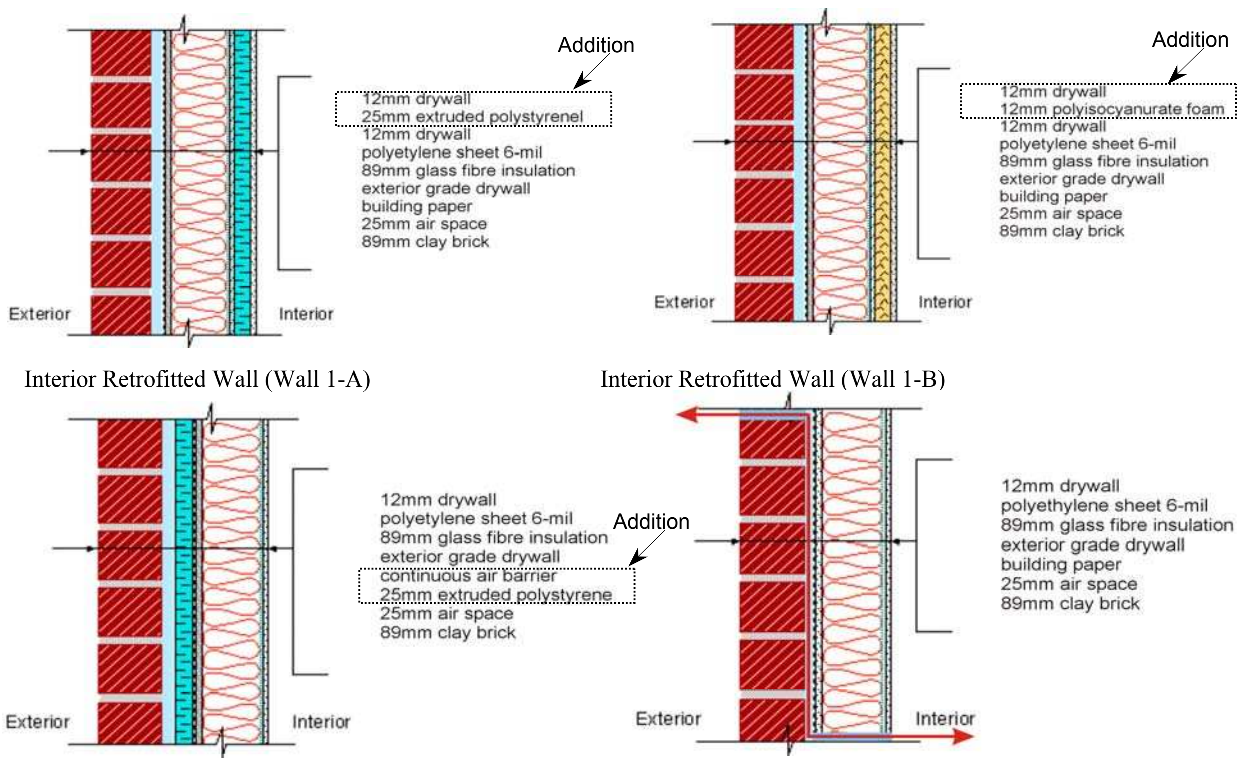


Figure 1: Base Case Wall 1 (Brick Veneer - Steel Stud)



Interior Retrofitted Wall (Wall 1-A)

Interior Retrofitted Wall (Wall 1-B)

Interior and Exterior Retrofitted Wall (Wall 1-C)

Air Sealing Retrofitted Wall (Wall 1-D)

Figure 2 – Base Case and Retrofitted Brick Veneer - Steel Stud Wall Assemblies

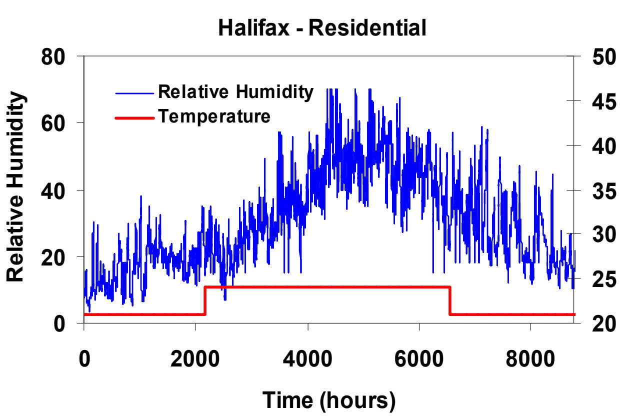


Figure 3 – Typical indoor Temperature and Relative Humidity (Halifax)

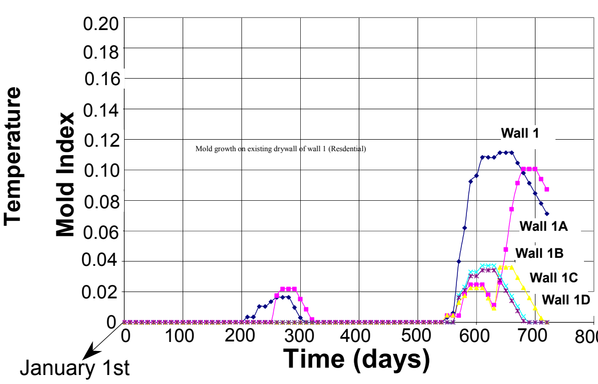


Figure 4 - 'Mold Index' Development in Existing Drywall (Halifax)

Yearly Heat Balance Across the Envelope

The values of total heat balance for the third year of the simulation period across each wall assembly (both base case and retrofitted options) are calculated in this study. These total values for the yearly heat balance include both heat loss and gain over a period of time.

RHTT Index

The potential for any moisture damage when sustained high moisture levels and warm temperatures occur simultaneously for an extended period of time. Such conditions are favourable for the initiation of corrosion, swelling and expansion, efflorescence/subflorescence, and biological damage in the building envelope and its components. The RHTT index, as defined below, indicates the presence of such favourable conditions.

The RHTT index, as used in *hygIRC-2D*, is defined as the product of two terms (see Equation 1). The first term represents the time factor, the time-of-wetness (TOW). The degree of moisture damage due to any of the four types of degradation mechanisms, mentioned above, is directly proportional to TOW. The second term represents the intensity of hygrothermal loading level in the envelope component by which the critical conditions are exceeded. This second term is the same as the RHT index described in *Kumaran et al. 2003; Mukhopadhyaya et al. 2003*.

$$RHTT(i,j) = TOW\,(i,j) \times RHT(i,j) \qquad [1]$$

where, *TOW(i, j)* is the calculated time of wetness within the considered part of the envelope component (%) and *RHT(i, j)* is the calculated RHT index within the considered part of the envelope component. The time of wetness, or TOW, is defined as the fraction of the year when the relative humidity is above 80% and the temperatures are above the critical temperature $T_{crictial}$. The summation is performed for the last year (i.e. third year) of the calculation.

The RHT index is calculated by multiplying the two terms, temperature potential ($T_{potential}$) and moisture ($\phi_{potential}$), for moisture damage (see Equation 2).

$$RHT(i,j) = \sum_{1}^{8760\,hours} T_{potential}(i,j) \times \phi_{potential}(i,j) \qquad [2]$$

where

$$T_{potential}(i,j) = T(i,j) - T_{critical} \quad \text{if } T(i,j) > T_{critical}$$
$$T_{potential}(i,j) = 0 \quad \text{if } T(i,j) < T_{critical}$$
$$T_{potential}(i,j) = \phi(i,j) - \phi_{critical} \quad \text{if } \phi(i,j) > \phi_{critical}$$
$$\phi_{potential}(i,j) = 0 \quad \text{if } \phi(i,j) < \phi_{critical}$$

where, $T_{potential}(i,j)$ = temperature potential for moisture damage (K); $\phi_{potential}$ = moisture potential for moisture damage (%); $T_{critical}$ = critical temperature level above which moisture damage is more likely to occur (K); $\phi_{critical}$ = critical relative humidity level above which moisture damage is more likely to occur (K).

The critical temperature and relative humidity vary depending on the nature of the construction material being considered and moisture damage involved. For example, biological deterioration of interior drywall due to mould growth may require higher temperature and lower relative humidity, depending on the fungal species involved. Efflorescence/subflorescence and swelling/expansion may also need higher hygrothermal levels. On other hand, active corrosion of metal components may occur when temperatures are just above the freezing point, depending on the material and the surrounding chemical agents.

In this study, two values of RHTT index (RHTT1 and RHTT2) were calculated using critical relative humidity ($\phi_{critical}$) of 80 percent and temperature ($T_{critical}$) level of 5°C for RHTT1 to examine the potential for biological growth, and using critical relative humidity ($\phi_{critical}$) of 80 percent and temperature ($T_{critical}$) level of 0°C for RHTT2 to examine the potential for corrosion in metals.

It is to be noted here that though the concepts of RHTT1 and RHTT2 indices have been established the acceptable or safe values for these indices for various building materials are not available at this moment.

Freeze-Thaw Index

The freeze-thaw index (FT) is defined as the number of cycles when temperatures oscillate between the freezing and thawing point for those envelope components that are almost at the moisture saturation level, $\phi_{critical}$. The summation is performed for the last year of the calculation. The higher number of cycles indicates greater potential for freeze-thaw damage. The freeze-thaw index is defined in Equation 3.

$$FT(i,j) = \sum_{2}^{8760\,hours} Cycle(i,j) \qquad [3]$$

where,

$Cycle(i,j)=1$ if $T(i,j,k)*T(i,j,k-1) < 0$ and $\phi(i,j,k) > \phi_{critical}$

$Cycle(i,j)=0$ if $T(i,j,k)*T(i,j,k-1) > 0$ and $\phi(i,j,k) < \phi_{critical}$

where,

$T(i,j,k)$	calculated temperature within the considered part of the envelope component at a particular time step (k)
$\phi(i,j,k)$	calculated relative humidity within the considered part of the envelope component at a particular time step (%)
$\phi_{critical}$	critical moisture saturation level in the envelope component (%)
i j	spatial indices for the considered part of the envelope component
k	considered time step index

The critical moisture saturation level, $\phi_{critical}$, varies depending on the nature of the construction material being considered. Further investigation is necessary to establish $\phi_{critical}$ for different construction materials. For this study, a value of 95% relative humidity is assumed for frost damage to occur.

Long-Term Performance of Wall

Researchers at the IRC/NRC have been working on a methodology that uses the hygrothermal simulation outputs (temperature, relative humidity) to assess the risk of mold growth in various components of wall systems (*Nofal and Tariku 2002*). The typical mold risk assessment is based on the definition of 'Mold Index' as shown in Table 1 (*Nofal and Tariku 2002*). The acceptable or safe values of 'Mold Index' are available only for a few building materials (mostly from Europe) such as wood and gypsum board. Further research is necessary to establish the acceptable or safe 'Mold Index' values for various building materials used in North America.

RESULTS AND DISCUSSION

The percentage reductions of heat loss (i.e. interior to exterior), air leakage reduction, and 'Mold Index' for the base case and retrofitted wall assemblies at all five geographical locations are shown in Table 2. The higher value of percentage heat balance reduction indicates a more energy efficient wall retrofit option. The results show that Retrofit option 1B has the highest heat balance reduction. Retrofit options 1A and 1C have heat balance reductions similar, but less than option 1B. However, retrofit option 1D has considerable lower amount of heat balance reduction compared to other three retrofit options.

The maximum values of RHTT1, RHTT2 and FT indices for each wall system and wall component are shown in Table 3. Lower values of these indices indicate lesser damage potential due to hygrothermal loading.

Typical 'Mold Index' development curves in the existing drywall for the walls 1, 1A, 1B, 1C and 1D at the location Halifax (Shearwater) are shown in Figure 4. Table 2 presents the 'Mold Index' in the existing drywall for each of the wall retrofit options. The base case and all of the retrofit options show no risk for mold development in the existing drywall.

Based on the results presented in Tables 2 and 3, the retrofit options 1-A, 1-B and 1-C are the most performing choices based on their moisture and energy performances. However, one has to be careful about the retrofit option in Winnipeg. Retrofit option 1-C shows significantly higher freeze-thaw index in the exterior XPS in Winnipeg. Retrofit option 1-D has almost a similar moisture performance but a much lower improved energy performance as compared to the other three identified retrofit options. This presents the dilemma in recommending one optimized retrofit option, even at one location, let alone a general recommendation for a given wall.

CONCLUSIONS

It is evident from the results presented and discussed in this report that retrofitted wall assemblies show either improved moisture management capability or improved energy (thermal) performance or both. However, it is not always possible to single out one retrofit option as the most desirable retrofit option at each location. Nevertheless this research project has achieved a number of objectives that were set as primary goals at the time of conception of the research proposal. In general the following are the major contributions delivered from this study.

(1) It has been shown that hygrothermal-modeling tool (e.g. *hygIRC-2D*) can be very versatile tool to optimize moisture and thermal design of building envelopes.

(2) A number of wall retrofit options have been identified that can be used as a guiding list by building practitioners and engineers for the selection of optimum retrofit options for the given masonry walls to simultaneously improve the moisture management capability and energy efficiency of the building envelope.

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Table 1 - Definitions and Rankings of Walls According to Mold Index

Mold index	Trend	Safety levels	Risk Level
M < 0.5	No increase	Optimum	No risk
0.5 < M < 1	Consistent increase	Safe	Low
1<= M < 1.5	No increase	Caution	Intermediate
M > 1.5	Consistent increase	Unacceptable	High risk

Table 2 – Air Leakage, Yearly Heat Balance and Mold Index

Location	Wall ID #	Mean Leakage Rates (L/s m^2)		Yearly Air leakage	Airflow Direction (%)		Yearly Heat Balance (W/m^2)	Heat Balance Reduction (%)	Mold Index in Existing Drywall
		Exfiltration	Infiltration	(L/m^2)	Exfiltration	Infiltration			
Halifax (Shearwater) (NS)	1	0.265	0.404	2631	75	25	97649	0	0.11 (No risk)
	1-A	0.158	0.242	1574	75	25	67009	31	0.10 (No risk)
	1-B	0.158	0.241	1570	75	25	65709	33	0.04 (No risk)
	1-C	0.159	0.243	1581	75	25	67629	31	0.02 (No risk)
	1-D	0.159	0.242	1574	75	25	76850	21	0.03 (No risk)
National Capital Region (Ottawa-Hull)	1	0.169	0.179	1503	77	23	81573	0	0 (No risk)
	1-A	0.101	0.107	895	77	23	56839	30	0 (No risk)
	1-B	0.100	0.107	892	77	23	55490	32	0 (No risk)
	1-C	0.101	0.108	898	77	23	57432	30	0 (No risk)
	1-D	0.101	0.107	897	77	23	67595	17	0 (No risk)
Toronto (ON)	1	0.202	0.237	1835	78	22	88119	0	0.02 (No risk)
	1-A	0.120	0.142	1096	78	22	61100	31	0 (No risk)
	1-B	0.120	0.142	1092	78	22	59748	32	0 (No risk)
	1-C	0.121	0.143	1100	78	22	61736	30	0 (No risk)
	1-D	0.120	0.142	1096	78	22	71757	19	0 (No risk)
Winnipeg (Man)	1	0.228	0.311	2288	61	39	97749	0	0.02 (No risk)
	1-A	0.135	0.187	1365	61	39	68006	30	0.12 (No risk)
	1-B	0.135	0.187	1361	61	39	66488	32	0.12 (No risk)
	1-C	0.135	0.188	1369	61	39	68513	30	0 (No risk)
	1-D	0.135	0.187	1364	61	39	80058	18	0 (No risk)
Vancouver (BC)	1	0.127	0.162	1231	62	38	58320	0	0 (No risk)
	1-A	0.076	0.097	737	62	38	40428	31	0 (No risk)
	1-B	0.076	0.097	735	62	38	39519	32	0 (No risk)
	1-C	0.076	0.097	740	62	38	40818	30	0 (No risk)
	1-D	0.076	0.097	737	62	38	47562	18	0 (No risk)

Table 3 – RHTT and Freeze-Thaw (FT) Indices

Wall	Comp-onent*	Shearwater			NCR (Ottawa – Hull)			Toronto			Winnipeg			Vancouver		
		RHTT1	RHTT2	FT	RHTT1	RHTT2	FT	RHTT1	RHTT2	FT	RHTT1	RHTT2	FT	RHTT1	RHTT2	FT
1	ED	3.52E-02	3.67E-04	0	1.63E-02	1.23E-02	0	2.08E-02	1.53E-02	0	1.42E-03	1.22E-03	0	3.58E-03	2.09E-03	0
	GF	4.12E-02	2.06E-02	13	3.81E-02	3.35E-02	5	2.58E-02	3.46E-03	3	5.64E-02	4.75E-02	12	1.49E-01	6.49E-02	1
	EG	3.68E-02	2.43E-02	13	7.39E-02	5.97E-02	6	2.88E-02	2.39E-02	1	6.07E-02	5.10E-02	4	1.58E-01	1.12E-01	1
	BP	3.89E-02	2.61E-02	13	7.35E-02	5.75E-02	5	3.86E-02	3.00E-02	4	5.15E-02	4.59E-02	6	1.56E-01	1.07E-01	1
	CB	1.45E-01	9.66E-02	25	1.72E-01	1.23E-01	15	1.58E-01	1.14E-01	21	1.43E-01	1.06E-01	15	2.25E-01	1.27E-01	2
1-A	ED	3.30E-02	2.64E-02	0	1.51E-02	1.12E-02	0	8.27E-03	6.98E-03	0	5.56E-02	4.73E-02	0	1.78E-02	1.18E-02	0
	RD	2.11E-02	2.74E-04	0	7.38E-03	5.70E-03	0	9.01E-03	6.84E-03	0	6.09E-03	4.64E-03	0	6.37E-04	4.51E-04	0
	GF	3.70E-02	8.36E-02	12	4.94E-02	4.34E-02	9	3.29E-02	2.48E-02	14	8.64E-02	3.06E-02	17	9.31E-02	1.13E-01	1
	EG	1.23E-01	8.45E-02	12	8.23E-02	4.78E-02	8	3.80E-02	2.93E-02	14	8.92E-02	7.18E-02	14	1.15E-01	7.72E-02	1
	BP	5.12E-02	8.92E-02	12	8.30E-02	6.51E-02	7	4.73E-02	3.67E-02	14	9.76E-02	7.50E-02	17	1.59E-01	1.08E-01	1
	CB	1.44E-01	9.70E-02	25	1.73E-01	1.24E-01	17	1.56E-01	1.15E-01	20	1.43E-01	1.06E-01	16	2.17E-01	1.25E-01	2
	EP	2.22E-02	6.85E-04	1	6.10E-03	4.66E-03	0	7.00E-03	5.92E-03	0	5.21E-02	4.44E-02	0	1.14E-02	7.50E-03	0
1-B	ED	2.69E-02	2.13E-02	0	1.56E-02	1.17E-02	0	6.66E-03	5.60E-03	0	4.92E-02	4.18E-02	0	1.86E-02	1.22E-02	0
	RD	2.11E-02	1.53E-02	0	7.37E-03	5.70E-03	0	8.97E-03	6.81E-03	0	6.08E-03	4.64E-03	0	6.33E-04	4.49E-04	0
	GF	3.72E-02	8.38E-02	12	5.03E-02	4.42E-02	10	3.31E-02	2.49E-02	14	3.64E-02	3.19E-02	17	9.39E-02	1.14E-01	1
	EG	1.24E-01	8.46E-02	12	8.28E-02	4.80E-02	7	3.79E-02	2.94E-02	14	8.88E-02	7.15E-02	14	1.16E-01	7.75E-02	1
	BP	5.15E-02	8.93E-02	12	8.34E-02	6.53E-02	7	4.76E-02	3.70E-02	14	9.81E-02	7.53E-02	18	1.59E-01	1.08E-01	1
	CB	1.44E-01	9.69E-02	25	1.74E-01	1.24E-01	17	1.56E-01	1.15E-01	20	1.43E-01	1.06E-01	16	2.17E-01	1.25E-01	2
	PI	2.19E-02	6.74E-04	0	6.02E-03	4.60E-03	0	5.65E-03	4.76E-03	1	4.63E-02	3.93E-02	0	1.20E-02	7.87E-03	0
1-C	ED	2.21E-02	1.59E-02	0	7.76E-03	5.98E-03	0	9.60E-03	7.26E-03	0	6.73E-03	5.13E-03	0	7.68E-04	5.42E-04	0
	GF	7.77E-02	5.92E-02	15	1.00E-01	5.49E-02	6	4.76E-02	5.09E-02	11	3.89E-02	3.42E-02	15	1.66E-01	1.18E-01	0
	EG	9.06E-02	6.57E-02	8	1.10E-01	8.69E-02	3	7.27E-02	5.83E-02	6	1.17E-01	9.23E-02	13	1.76E-01	1.25E-01	0
	CB	1.43E-01	9.64E-02	25	1.73E-01	1.24E-01	17	1.56E-01	1.15E-01	20	1.43E-01	1.06E-01	17	2.18E-01	1.25E-01	2
	EP	4.93E-02	9.05E-02	12	6.77E-02	4.76E-02	10	3.98E-02	3.02E-02	14	1.15E-01	5.23E-02	25	1.16E-01	7.56E-02	1
1-D	ED	2.17E-02	1.57E-02	0	7.56E-03	5.83E-03	0	9.36E-03	7.08E-03	0	6.41E-03	4.88E-03	0	7.18E-04	5.06E-04	0
	GF	3.38E-02	8.13E-02	12	4.36E-02	3.84E-02	9	2.12E-02	1.87E-02	11	2.61E-02	2.29E-02	13	8.12E-02	1.11E-01	1
	EG	3.77E-02	8.30E-02	12	5.65E-02	4.38E-02	9	3.00E-02	2.73E-02	12	7.78E-02	6.38E-02	10	1.06E-01	7.08E-02	1
	BP	4.61E-02	8.78E-02	11	7.56E-02	5.91E-02	8	4.28E-02	3.33E-02	11	8.46E-02	6.55E-02	11	1.47E-01	9.99E-02	1
	CB	1.46E-01	9.59E-02	25	1.74E-01	1.25E-01	17	1.58E-01	1.14E-01	20	1.44E-01	1.06E-01	16	2.18E-01	1.27E-01	2

* - ED: Existing Drywall; GF: Glass Fiber; EG: Exterior Gypsum; BP: Building Paper; CB: Clay Brick; RD: Retrofit Drywall; EP: Extruded Polystyrene; PI: Polyisocyanurate