Lower-Technology, Higher-Performance Construction

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Abstract

This grant research is focused on lower-technology, higher-performance construction systems. Such an approach improves the performance of design practices and buildings not by adding ever-increasing layers of technology, systems, intricacy, specificity and coordination to our practices and buildings but rather by questioning and strategically editing the unwarranted complexity that dominates our buildings, practices, and lives. Today, given current economic and ecological realities, there is considerable efficacy in de-escalating building technology and systems in order to advance practice. An optimal approach to de-escalation is through more solid and simple monolithic construction systems that are yet capable of exceeding the performance perhaps evident in a multi-layered, higher-technology building. Further, such simpler assemblies also engender the critical capacities of durability, adaptability, and resilience generally not possible in the excessively additive mentality of contemporary construction logics that are driven by a dynamic of obsolescence. A shift to lower-technology, higher-performance approaches stands to trigger a set of systemic benefits for our buildings and practices that will advance practice in this century. Buildings and their architects can and must do much more with much less in this century.

Practice Context:

A major enabler, and consequence, of lower-technology buildings is more simple and sane design practices. The logic of contemporary construction follows an excessively additive mentality: for each task or problem, a new layer, lawyer, system, consultant, pile of construction and shop drawings, and/or layer of coordination is added. Contemporary construction also follows an ecologically exasperating dynamic of obsolescence. This is a major and unwarranted roadblock to sustainable practices. Likewise, while Building Information Modeling (BIM) was developed to manage the ever-increasing layers of complexity and coordination inherent in current building projects, it only addresses the symptomatic issues of contemporary practices, not the core problem. This trend is professionally unsustainable. A building with fewer and simpler systems demands deeper and more deliberate integration—an architectural and ecological solution—not just an enabling software amelioration.

Thus, a primary impetus of this research is that architects should know much more about doing much less and, in turn, achieving much more. This research helps explicate some fundamental building science that has been overlooked, ignored, dismissed, or otherwise neglected in the development of modern, lightweight construction systems.

There are several roadblocks to the implementation of lower-technology, higher-performance approaches. The aim of this research report is to help provide some of theoretical and practical parameters that are involved with lower-technology approaches. This documentation will be part of a larger book effort on this topic. The first section of this report analyses 1 typical and 4 lower-technology, higher-performance construction types in a range of software and other quantitative means. Based on the observations of this first section, the second section investigates a couple of these construction types in great detail and with more parameters.

1. Software Analysis of Lower-Technology Systems:

WUFI Analysis:

WUFI is a 1-D, steady state moisture and heat calculator. It is particularly useful for studying vapor transmission and liquid transmission in building envelopes. It is climate specific and runs the dynamics of a typical three year period. As the model runs and with the final output data, it is possible to determine key properties of the wall assembly such as total water and vapor content, the relationship of dew point temperature and dry bulb temperature, and interior and exterior surface temperatures. The WUFI analysis here looks at comparative wall assemblies. The first case is a typical stick approach to construction: lumber construction with layers of insulation plywood, and a rainscreen enclosure. The other cases look at monolithic systems, each 12" thick for the purposes of comparison. For the purposes of this comparison, a Boulder, Colorado climate data set was used.

WUFI summary	total water content				Amount of drying %	Interior Surface Temp		
	start	end	min	max		Low °F	High °F	Flux
Stick, Layered Construction	0.65	0.31	0.26	0.65	48%	68	87	19
Masonry	0.15	0.09	0.08	0.23	60%	62	86	24
CLT	3.49	1.57	1.57	3.49	45%	61	79	18
Lightweight Air Entrained Concrete	1.13	0.33	0.26	1.13	29%	63	73	10
Concrete SIP	1.62	1.19	1.15	1.62	73%	63	72	9

From a thermal point of view, the masonry system exhibited great flux during the model run. This is not a surprise, nor is the performance of the well-insulated concrete SIP panel. This concrete offers an optimal combination of insulation effects as well as mass effects. The lightweight air-entrained concrete performed quite thermally and in terms of moisture. A wall constructed with this monolithic material is quite thick because the lower PSI of lightweight concrete requires more mass to perform structurally. This thickness, in turn, uses the millions of entrained air pockets as its insulation strategy as well as to manage vapor and dew point condensation with its capacity to 'breath' once psychrometric conditions have changed.

THERM Analysis:

THERM is a two-dimensional heat transfer modeling software program. It is especially useful for studying thermal bridges. It is finite-element analysis of thermal flux in a given assembly and is used widely to model the performance of window frame assemblies, wall assemblies, and, importantly, foundation/wall/roof junctures. The THERM analysis looks are the same set of wall systems, this time looking at a corner condition, using THERM's 2-D capacity. The results confirm intuition but illuminate a few key issues with a low interior surface temperature (~51°F). The masonry system again performs poorly in this thermal milieu. The stick system provides for a warm but uneven surface temperature (~66°F). The solid wood system works well with a slightly lower, but more consistent surface temperature (64.5°F). The homogeneous lightweight concrete system is also consistent but cooler (60°F). The concrete SIP system performs the best with a 66°F+ surface temperature. It is important to note that THERM does not take account of a normal milieu; like WUFI, THERM assumes a steady-state condition. This demands an alternate, analog approach that includes more factors. This will occur in a subsequent section.

Embodied Energy (EE) Analysis:

Rome has some of the most sustainable, integrated buildings in the world. This is not on account of many decades of exuberant, high-technology buildings with layers and layers of systems and technologies but rather a pervasive and persistent practice of durability and re-use over the millennia. In Rome, the ecological and economic amortization of the low-embodied energy and low-operational energy of its building stock divided by the generations it has served through the centuries strikes a sharp contrast with a contemporary, higher-technology, higher-embodied energy building that will serve a limited population for thirty to, perhaps, a hundred years. When this amortization is coupled with its correlate—the cultural and social dividends of those resources returned over the same period—the basis of multiple forms of sustainability and humanity is evident. The embodied energy analysis also looked at a comparative wall system. Given the quantities of material in each construction system of the same size, standard embodied energy values given for each construction system. The following table summarizes this analysis:

Embodied Energy of Wall Types

Stick/Layered	qty	length	linear feet	volume per	feet^3	meters^3	EE (MJ per unit)	Total EE (MJ)	Equal (MJ)	Required Lifespan (years)
Wall Framing: 2x6 stud	39	18.2	710	0.06	40.66	1.15				
Wall Framing: 2x6 plate	2	36	72	0.06	4.12	0.12				
Wall Framing: blocking	76	0.875	67	0.06	3.81	0.11				
Wall Framing: 2x12 beam	3	36	108	0.11	12.37	0.35				
Wall Framing: total					60.97	1.73	4692	**8101**		
Plywood: 1/2"	23			1.33	30.66	0.87	9440	**8195**		
Batt Insulation: R-19 x 12"	36	18	648		162.00	73.50	150	**11025**		
Interior Finish: 1x6 SYP #1	39	36	1404	0.02	26.80	0.76	4692	**3561**		
Rain Screen: 2x4 nailer	19	19.2	365	0.03	10.45	0.30				
Rain Screen: 2x6 cladding	39	36	1404	0.06	80.44	2.28				
Rain Screen: total						2.57	4692	**12075**		
Stick Total Embodied Energy								**42958**	**250**	***172***

Solid Wood	rows	length	linear feet	volume per	cu feet	cu meter	MJ per unit	MJ	Equal (MJ)	Required Lifespan (years)
6x8 timber	31	36	1116	0.28	309.03	8.75	638	**5583**		
Solid Wood Total Embodied Energy								**5583**	**250**	***22***

Lightweight, Air-Entrained Concrete	cu feet	cu meter	MJ per unit	MJ	Equal (MJ)	Required Lifespan (years)
12" of solid concrete	697.50	19.75	2350	**46415**		
Lightweight Concrete Total Embodied Energy				**46415**	**250**	***186***

Load Bearing Masonry	cu feet	cu meter	MJ per unit	MJ	Equal (MJ)	Required Lifespan (years)
brick	523.75	14.83	5170	**76676**		
mortar	161.38	4.57	15210	**69506**		
Masonry Total Embodied Energy				**146182**	**250**	***585***

Concrete SIP	area	height	area	height	cu feet	cu meter	MJ per unit	MJ	Equal (MJ)	Required Lifespan (years)
Concrete	18.25	18	36	1.375	378	10.70	3180	**34038**		
6" rigid insulation	17.75	18			319.50	9.05	2340	**21171**		
Concrete SIP Total Embodied Energy								**34038**	**250**	***136***

Embodied Carbon (EC) Analysis:

It is equally illuminating to study the embodied carbon content for each of the material systems. Most of the systems share a similar amount of embodied carbon. The concrete SIP panel systems as much higher value here due to the large amount of rigid insulation. A further cost/benefit analysis of its thermal performance over time would offset the carbon costs of the insulation.

Embodied Carbon of Wall Types

Stick/Layered	qty	length	linear feet	volume per	feet³	meters³	weight (lbs/ft³)	Kg	EC (KgCO2/Kg)	Total EC (Kg CO_2)	Equal EC/ (Kg CO2)	Required Lifespan (years)
Wall Framing: 2x6 stud	39	18.2	710	0.06	40.66	1.15	1382.59	627.13				
Wall Framing: 2x6 plate	2	36	72	0.06	4.12	0.12	140.25	63.61				
Wall Framing: blocking	76	0.875	67	0.06	3.81	0.11	129.53	58.76				
Wall Framing: 2x12 beam	3	36	108	0.11	12.37	0.35	420.74	190.84				
Wall Framing: total					60.97	1.73	2073.11	940.35	0.45	**423.16**		
Plywood: 1/2"	23			1.33	30.66	0.87	1045.12	474.06	0.81	**383.99**		
Batt Insulation: R-19 x 12"	36	18	648		162.00	73.50	324.00	146.96	1.35	**198.40**		
Interior Finish: 1x6 SYP #1	39	36	1404	0.02	26.80	0.76	804.07	364.72	0.45	**164.12**		
Rain Screen: 2x4 nailer	19	19.2	365	0.03	10.45	0.30	355.29	161.16	0.45	**72.52**		
Rain Screen: 2x6 cladding	39	36	1404	0.06	80.44	2.28	2734.80	1240.48	0.45	**558.22**		
Stick Total Embodied Energy										**1800**	**100**	**18**

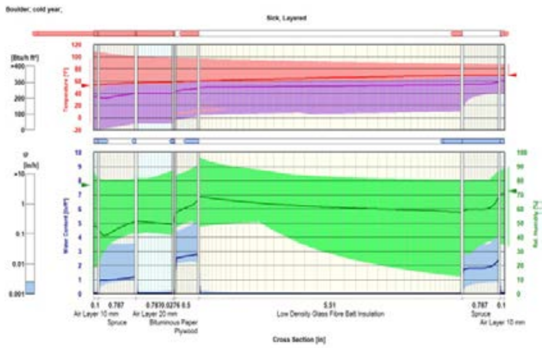
Solid Wood	rows	length	linear feet	volume per	cu feet	meters³	weight	Kg	EC (KgCO2/Kg)	Total EC (Kg CO_2)		
6x8 timber	31	36	1116	0.28	309.03	8.75	8652.85	3924.87	0.45	**1766.19**		
Solid Wood Total Embodied Energy										**1766**	**100**	**18**

Lightweight, Air-Entrained Concrete	cu feet	weight	Kg	EC (KgCO2/Kg)	Total EC (Kg CO_2)		
12" of solid concrete	697.50	20925.00	9491.42	0.096	**2009**		
Lightweight Concrete Total Embodied Energy					**2009**	**100**	**20**

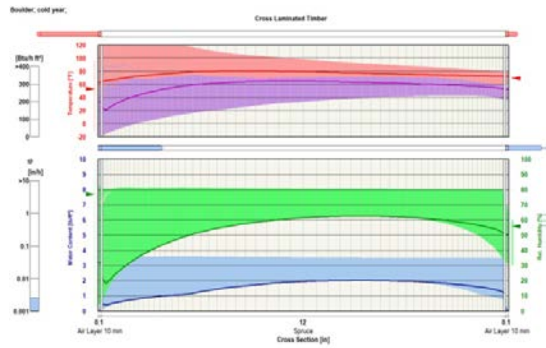
Load Bearing Masonry	cu feet	weight	Kg	EC (KgCO2/Kg)	Total EC (Kg CO_2)		
brick	523.75	15712.50	7127.07	0.22	**3457**		
mortar	161.38	4841.40	2196.02	0.163	**789**		
Masonry Total Embodied Energy					**4246**	**100**	**42**

Concrete SIP	area	height	area	height	cu feet	weight	Kg	EC (KgCO2/Kg)	Total EC (Kg CO_2)		
Concrete	18.25	18	36	1.375	378	11340.00	5143.74	0.13	**1474**		
6" rigid insulation	17.75	18			319.50	9585.00	4347.68	2.5	**23963**		
Concrete SIP Total Embodied Energy									**25437**	**100**	**254**

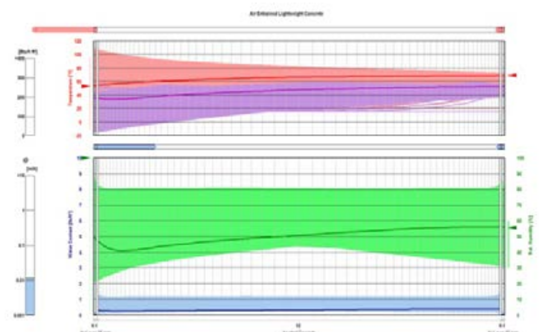
WUFI Analysis figures:



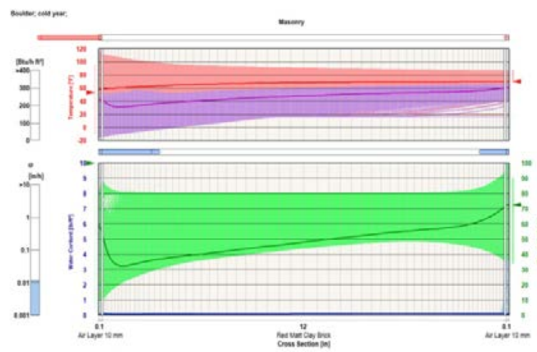
1. Stick Framed WUFI analysis



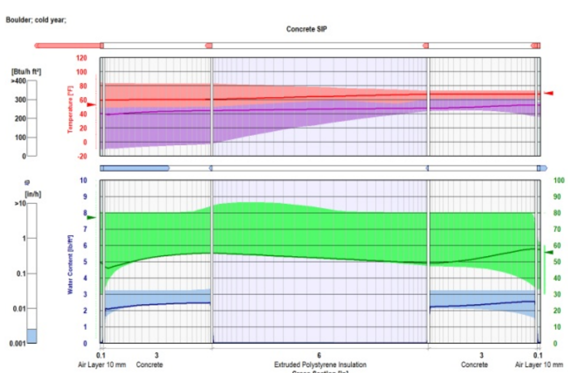
2. Solid Wood WUFI analysis



3. Lightweight Concrete WUFI analysis

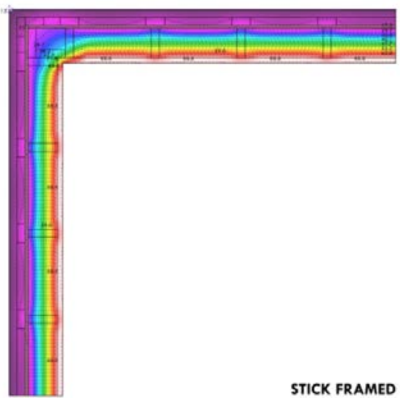


4. Load Bearing Masonry WUFI analysis

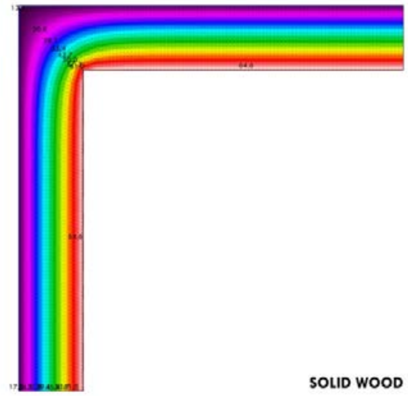


5. Concrete SIP WUFI analysis

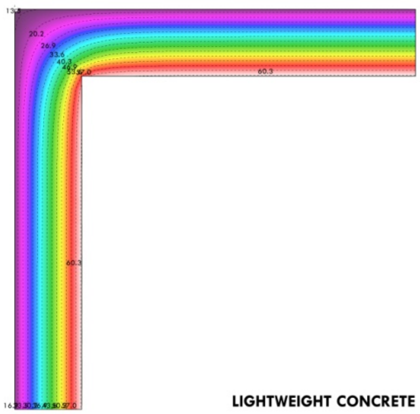
THERM Analysis figures:



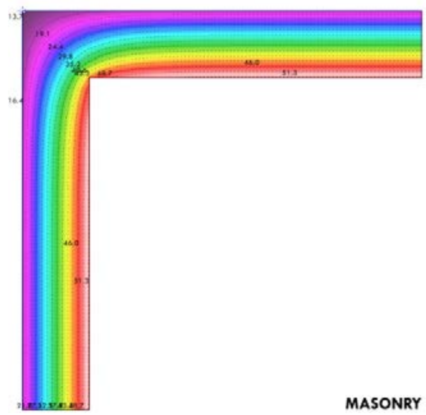
1. Stick Framed THERM analysis



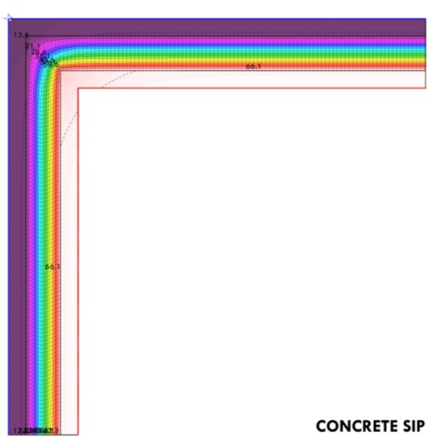
2. Solid Wood THERM analysis



3. Lightweight Concrete THERM analysis



4. Bearing Masonry THERM analysis



5. Concrete SIP THERM analysis

2. Building Science of Lower-Technology Systems:

In most cases, lower-technology, higher-performance systems are simpler and monolithic construction systems such as air-entrained concrete, concrete SIPs, brick masonry, and solid wood types. The role of thermal conductivity is very important, but only under steady state conditions. Such conditions occur in buildings and their milieus, especially in lightweight assemblies (one reason for the unwarranted focus on “R”-values in the North American building industry). However, the reality is that any building material has mass and thus other parameters are important. Architects may know that a metal, such as copper, has a much great thermal conductivity value than concrete and that concrete conducts more heat energy than glass, wood and plastic insulations. Few, if any, architects know that glass and plastic insulations have the same thermal diffusivity, much less the implications of this fact. The reality is that buildings and their milieus are not steady-state conditions. They are in constant thermal flux. Thus, the role of thermal conductivity is perhaps, at best, a generalization of relative, hypothetical performance. But it is not an indicator of building performance. Since building milieus are in constant flux, a time-dependent characterization of buildings is required. This requires the incorporation of two thermal properties: thermal diffusivity and thermal effusivity.

Observations from WUFI, THERM, EE, EC Analysis:

In the dendritic decision path of selecting lower-technology systems, the embodied energy analysis reveals some straightforward information. For instance, the high embodied energy of a masonry assembly and a typical stick-framed approach to a wall make little sense compared to the lower embodied energy values of the other systems. The embodied energy of the masonry wall case is significantly higher than a renewable source, such as wood. As a comparison, a masonry building needs to be a 585 year building compared to a 22 year wood building before it is a equally viable option over its lifetime. Other information is revealed when the embodied energy values are speculatively rationed over their lifetime. This EE/lifespan value points towards broader views of performance. Taken the embodied energy analysis together, it appears that the concrete systems and solid wood cases make the most sense. To summarize the results, the performance of each system in each analysis was ranked (5 is the best). For the purposes of this study, solid wood (cross laminated timber) on average performs best for this range of performance criteria.

	$WUFI_m$	$WUFI_t$	Therm	EE	EC	Total
Stick, Layered Construction	3	2	4	3	4	16.00
Masonry	2	1	1	1	2	7.00
CLT	4	3	3	5	5	20.00
Lightweight Air Entrained Concrete	5	4	2	2	3	16.00
Concrete SIP	1	5	5	4	1	16.00

In each of the types of analysis, these materials exhibited favorable moisture and thermal performances. As such, the following section focuses on the optimization of the solid wood and the concrete systems. To do so, it is imperative to study a greater range of material and performance properties for these material assemblies. The above software relies primarily upon thermal conductivity as the operative behavior in the modeling. A first step is to assemble relevant material properties for a range of building materials. These are drawn from a number of sources. The following chart, strangely absent from books on building science, helps to more fully explicate the thermal properties of building materials:

Property:	Thermal conductivity[1]	Density	Specific Heat[2]	Volumetric heat capacity	Thermal diffusivity	Thermal Effusivity[3]
Notation:	k	ρ	c_p		a	e
Units:	W/mK	Kg/m^3	(J/kgK)	J/m^{3}K x 10^6	mm^2/s	w/cm^2/k/s$^{.5}$
Derivation:				equals specific heat capacity multiplied by the density	equals thermal conductivity / volumetric heat capacity	equals the square root of thermal conductivity * density *specific heat
Air	0.024	1.29	1012	0.0013	18.3840	0.000560
Aluminum Alloy	121	2740	795	2.1783	55.5479	1.623497
Brick	0.8	1900	840	1.5960	0.5013	0.112996
Concrete, dense	1.25	2200	750	1.6500	0.7576	0.143614
Concrete, Lightweight	0.2	750	960	0.7200	0.2778	0.037947
Copper	401	8960	385	3.4496	116.2454	3.719260
Cork	0.07	200	1900	0.3800	0.1842	0.016310
Foam Glass	0.045	120	840	0.1008	0.4464	0.006735
Glass	0.96	2600	840	2.1840	0.4396	0.144798
Marble	2.6	2700	880	2.3760	1.0943	0.248548
Mineral Wool Insulation	0.04	100	840	0.0840	0.4762	0.005797
Perlite	0.031	100	387	0.0387	0.8010	0.003464
Polystyrene, expanded	0.03	50	1300	0.0650	0.4615	0.004416
Polyurethane foam	0.03	30	1300	0.0390	0.7692	0.003421
Sandstone	1.7	2250	920	2.0700	0.8213	0.187590
Stainless Steel	16	7900	510	4.0290	3.9712	0.802895
Steel	43	7820	490	3.8318	11.2219	1.283618
Water	0.58	1000	4190	4.1900	0.1384	0.155891
Wood (Pine/Spruce)	0.12	450	2500	1.1250	0.1067	0.036742
Wood, Oak	0.17	750	2000	1.5000	0.1133	0.050498

1. http://www.engineeringtoolbox.com/thermal-conductivity-d_429.html
2. http://www.engineeringtoolbox.com/specific-heat-solids-d_154.html
3. http://www.electronics-cooling.com/2007/11/thermal-effusivity/

Discussion of Thermal Diffusivity and Effusivity in Building Design:

The thermal diffusivity of concrete and polyurethane foam is about .76 mm^2/s, yet their conductivity is quite different (concrete = 1.25 W/mK, polyurethane foam = .03 W/mK). Concrete's higher conductivity means that more energy moves through it more readily. However, since their volumetric heat capacities are also unequal (concrete = 1.65 $J/m^3K * 10^6$ and 0.0390 $J/m^3K * 10^6$, for polyurethane foam), it is apparent that the concrete will require more thermal energy to heat up.

To attain a more precise understanding of the performance of these lower-technology construction systems, it is necessary to factor in the role of thermal diffusivity. The following equations

Heat Content (Q) equations[i] for solid walls:

$Q = wpC_p\Delta T$ where:

w = wall thickness = $\sqrt{2at}$

$pC_p = volumetric\ specific\ heat\ capacity$

ΔT = temperature differential

$Q = \sqrt{2t}\Delta T a^{1/2} pC_p$ and substituting a (thermal diffusivity) = λ / pC_p provides:

$Q = \sqrt{2t}\Delta T(\frac{\lambda}{a^{1/2}})$

$M = \frac{\lambda}{a^{1/2}}$ = threshold of high volumetric heat capacity

$a \leq \frac{w^2}{2t}$ target thermal diffusivity

With the above equations, it is possible to project which materials, thicknesses, and time lags. Material, thickness, and time are variables here. By making an assumption about one variable, the other two are readily discernable. This parametric relationship between these variables can help guide early design decisions for lower-technology assemblies that can be studied in further detail. The following are a few examples cases:

(a) For thermal battery walls:

where w=.5m and time=12 hours (4×10^4 seconds)

$a \leq .5^2/2(3.6\ x\ 10^4)$ $= 3\ x\ 10^{-6}$

(b) For a thinner wall:

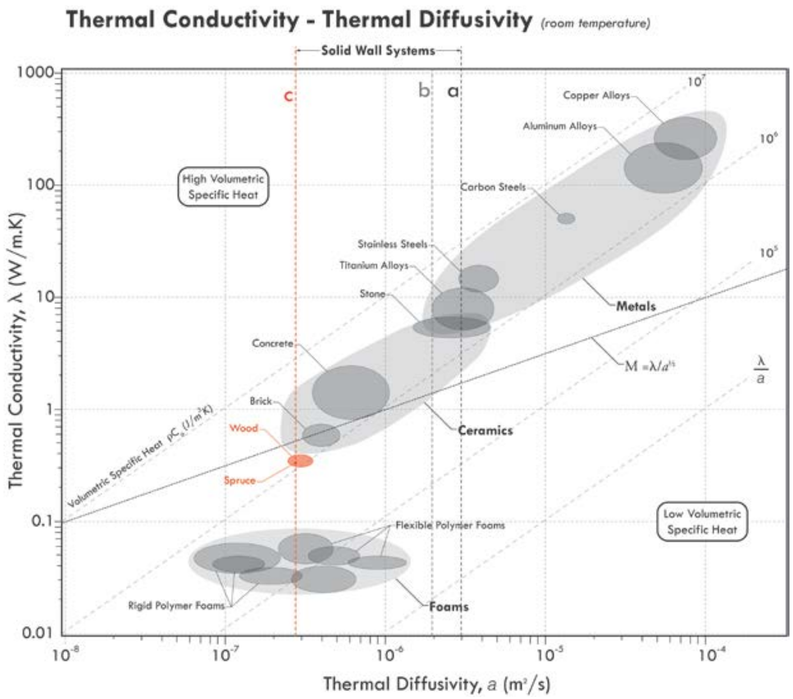
where w=.333m and time=10 hours (3.6×10^{-4} seconds)

$a \leq .333^2/2(3.6\ x\ 10^4)$ $=1.5\ x\ 10^{-6}$

(c) For softwood walls:

where w=.166m and time=12 hours (3.6×10^{-4} seconds)

$a \leq .166^2/2(3.6\ x\ 10^4)$ $=3.2\ x\ 10^{-7}$



Each of these cases is positioned on the following chart that visualizes relationships between thermal conductivity and thermal diffusivity. The above figure charts the thermal conductivity and diffusivity for common building materials. The solids (metals and ceramics) perform with similar volumetric specific heat capacities. Insulating foams are different. In this chart, line "b" indicates materials that perform well as the mass in a trombe wall. This assumes a wall about 18" thick and suggests that the materials with a higher volumetric heat capacity are good for this purpose. This confirms common assumptions about trombe walls and other thermal masses. What this chart reveals, however, is that by using materials with similar volumetric heat capacity but with lower conductivity and proportionally lower diffusivity can also work well. With wood (a cellular solid material that begins to approach the properties of a foam but nonetheless is a solid), thermal energy will take longer to diffuse thermal energy. Further, its proportionally lower effusivity suggests that it will also take wood longer to gain or release the heat. This positions solid wood assemblies in a new way. The cellular solid composition of wood, along with its relatively higher water content and pitch content, makes for a interesting and very complicated type of thermal performance.

Conclusion:

This research project aimed to explicate some the performance parameters for some lower-technology, higher-performance construction systems. These lower-technology construction types were contrasted in each type of analysis with a conventional stick framed wall. A primary contribution here is the inclusion of thermal diffusivity calculations. This is essential not only for advancing lower-technology approaches (in contrast to the "R"-value paradigm of current building science), but also to more accurate modeling of energy transfer in buildings. Current calculations leave out key aspects of the milieu such as thermal diffusivity and effusivity that can, and do, have an important determining influence on the comfort of bodies in built milieus.

Key Definitions:

Heat**:** a measure of the amount of energy transferred from one body to another given a temperature difference between them; energy flow caused by temperature differential. Not to be confused with internal thermal energy (the energy in a body). Heat focuses on the amount of energy transfer. Flow is always in the direction of the cooler body.

Specific Heat: the amount of energy required to increase the temperature of a certain unit mass of material by a temperature interval. This is a good indicator of the ability of a material to store thermal energy.

Thermal Conductivity**:** rate of steady-state flow of thermal energy through a material thickness. A material with high thermal conductivity in contact with outside air or in a thermal bridge will result in more energy transferred per unit time. In any milieu that is not a steady state (most conditions in and around buildings), time-dependent thermal properties should be used. Therefore, it is rather difficult to isolate and quantify thermal conductivity. It is difficult to understand why so much of building science focuses on conductivity and its inverse, resistivity (or "R" value).

Thermal Diffusivity**:** the rate of heat conduction within a volume of material. It is the ratio of thermal conductivity divided by volumetric heat capacity. Materials with a high thermal diffusivity distribute internal heat energy more rapidly than those with low thermal diffusivity.

Thermal Effusivity**:** material's ability to exchange heat with the environment. Imagine a piece of metal and a piece of wood in the same room at the same temperature. If you touch the piece of metal it feels colder than touching the wood because the effusivity of metal is higher than that of wood. Our bodies do not *measure* heat, they *sense* heat flux. The effusivity a material varies due to differences in heat transfer through and between its molecules. It is therefore a function of molecule properties: size, shape, density, crystallinity and moisture content.

$$a = \frac{k}{\rho c_p} \text{, and } e = \sqrt{k \cdot \rho c_p}$$

Thermal Lag: colloquial, metaphorical term used in architecture when non-steady state phenomena exists; used in lieu of thermal diffusivity and effusivity.

Volumetric Heat Capacity: the amount of energy required to increase the temperature of a certain volume of material by a temperature interval. It describes the ability of a given volume of a material to store internal energy while undergoing a temperature change (but not a phase change).

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[i] M. F. Ashby, *Material Selection in Mechanical Design*, third edition. Amsterdam; Boston: Elsevier Butterworth-Heinemann, 2005. pp. 154-157