FOUNDATIONS—THE BASE OF SUSTAINABLE RESIDENTIAL BUILDING DESIGN

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INTRODUCTION

The foundation is perhaps a building's most challenging envelope component from energy transport and hygrothermal perspectives. As such, the foundation literally provides the energy and materials basis on which the sustainability of the entire structure depends from a number of perspectives. The foundation can account for as much as 40% of the building envelope conduction loss and, more importantly, in unoccupied conditions, almost all of the latent load (or energy required for dehumidification). From a materials perspective, the foundation has to provide a durable interface between the surrounding ground and the building interior in the presence of bulk water, soil gasses (such as radon, water vapor, and even, on occasion, hydrogen sulphide), frost, biotic activity, and pest infestation while simultaneously being the building's structural basis. From an energy perspective, the foundation must insulate the interior from the surrounding soil and ambient environment, and provide an interior surface temperature producing comfortable conditions for the occupants while minimizing both sensible and latent thermal loads to the greatest possible extent.

Achieving all these requirements in a cost-competitive residential housing market is difficult. Certainly, national residential building codes such as the International Residential Code *(IRC) and the* International Energy Conservation Code *(IECC) do provide a least common denominator basis for building adequate foundations, but they do not go nearly far enough from a sustainability perspective, particularly in light of twenty-first century energy prerogatives. It is reasonable to state that these codes are a generation or two behind what would be an appropriate building regulatory policy for the current times, namely, that residential buildings in particular should be built to a zero net energy standard (that is, no net energy importation across the property line for a given calendar year). The technology to accomplish this standard does exist and is being demonstrated by agencies such as the United States Department of Energy (DOE).*

It is in this context that the State of Minnesota recently undertook a major revision of the foundation rules in its state energy code. The revision was prompted by widespread failures of foundation systems across the state, largely as a consequence of biotic activity caused by condensation within foundation wall assemblies. An example of the condensation that can be produced by wall assemblies compliant with Minnesota Rules chapter 7672.0600 is shown in Figure 1.

The energy code foundation rules revision was guided by the principle that the code rules must have an experimentally validated basis in the physics of building foundation heat and mass transport. The resultant rule as currently expressed in the public review draft (at the time of writing) has made significant progress in establishing a well-founded basis for constructing durable foundation systems that can fulfill the requirements of material and energy sustainability. Because the rule is centered on a set of generalized building envelope hygrothermal performance criteria, the rule is not limited to foundations in a cold climate, but is applicable to the entire envelope in all terrestrial climates.

RESEARCH BASIS

The genesis of the current generalized theory of foundation hygrothermal phenomenology was in the research and development of underground building technology that emerged in the late 1970s and progressed through the 1980s before petering out around 1995. One of the chief progenitors of this technology was the Underground Space Center at the University of Minnesota under whose auspices the University established the Foundation Test Facility (FTF) at UMore Park in Rosemount, MN. This facility currently consists of six foundation test modules, two slab-on-grade and four full basement, each having a 400 ft^2 footprint. These modules have been used over

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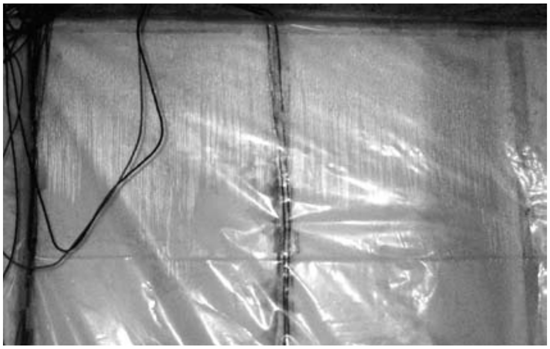
FIGURE 1. Condensation in mid-July with a grade-height polyethylene membrane between the stud frame and the wall, together with a full height interior (warm side) polyethylene membrane.



a 16-year period to test a very wide spectrum of foundation technologies ranging from frost-protected shallow foundations through the performance of variable permeance vapor retarding membranes (such as 2-mil. Polyamide-6) (BPFRP 2006). Examples of two interior foundation insulation systems tested are given in Figures 2 and 3. In 1997, the University's Cloquet Residential Research Facility came on line in Cloquet, MN, about 35 miles southwest of Duluth. This facility, located in a climate colder than that of the FTF, includes a two-zone, 2000 ft^2 basement that permits larger scale experimental studies to be undertaken.

These two facilities have provided the public domain experimental data on which analytic techniques

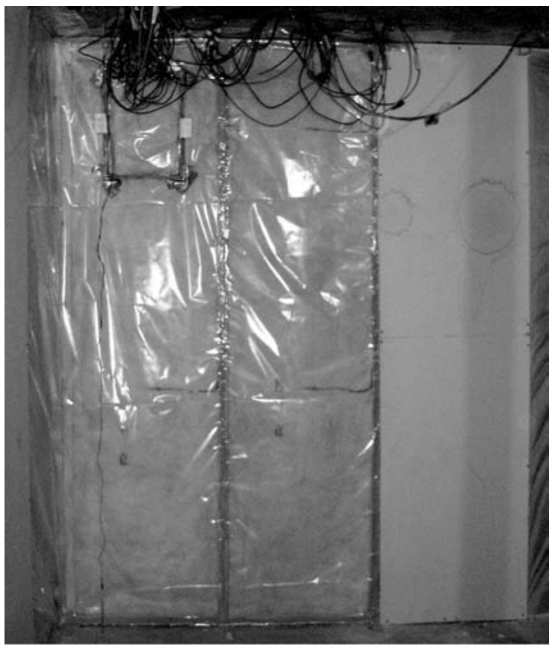
FIGURE 2. Test configuration for evaluating an insulation system using coarse-weave polyolefin covered semi-rigid fiberglass insulation.

for assessing the hygrothermal transport and energy performance of building foundations have been based. In addition to standard commercial computational fluid mechanics analyses and whole building energy simulation codes (such as the DOE *EnergyPlus* code), these techniques have included the development of a proprietary 3-dimensional geotechnical heat transfer code that includes quantum mechanical phase change modeling (Lofrango 2006).

An overview of the experimental energy performance of foundation systems can be summarized in terms of Figure 4 and Table 1 (BPFRP 2006)

The data in Figure 4 show the calorimetrically measured full basement energy consumption of the hollow masonry block west basement module at the FTF over a heating season normalized against the energy consumption of the north reference module. The reference module has an uninsulated poured concrete foundation envelope without reinforcing or footings. Neither basement has any waterproofing or vapor retarders as components of its static structure allowing these to be added as part of an experiment in order to isolate and study their hygrothermal performance. The basements are located in an engi-

FIGURE 3. Experimental evaluation of a 2-mil. polyamide-6 interior vapor retarder.



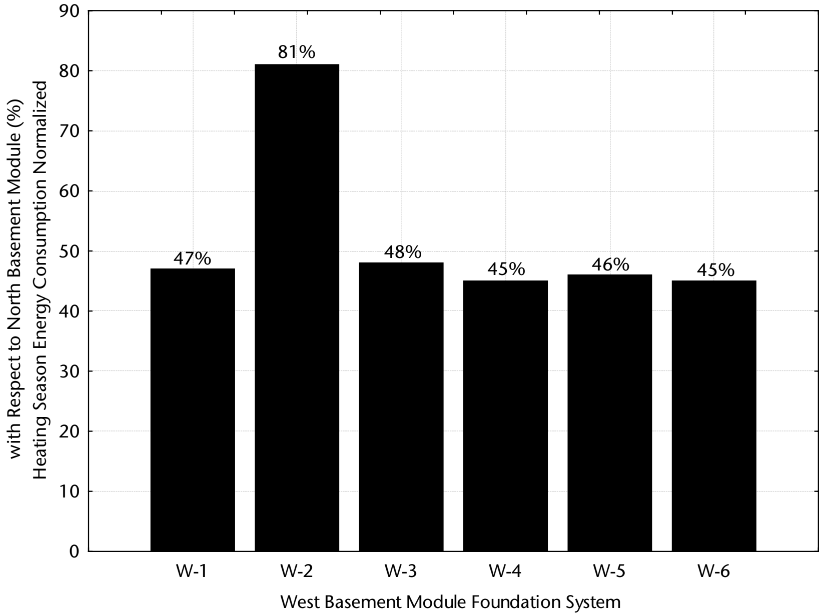


FIGURE 4. West basement module combined heating season thermal performance.

neered clean sand backfill, and the water table is about 80 ft. below grade.

It needs to be emphasized that all of the insulation systems in Figure 4 have a constant thickness over the entire wall surface in compliance with standard construction practice. In this context, the salient observation from Figure 4 is that as the insulation is varied from R_{US}-8 (W-3) through R_{US}-14 (W-5), the measured full basement (that is, including all 3-dimensional heat transfer effects) energy consumption remains constant within the bounds of the experimental error (±3%). The exception is much higher energy consumption of system W-2 that is a consequence of only the upper half of the walls being covered with interior insulation. The FTF data (replicated by computer simulations) also have shown that from a

TABLE 1. West basement module insulation system configurations.

Foundation system	Heating seasons	Insulation configuration	Vapor retarder configuration
W-1	1989/90, 1990/91	full-wall, interior R-10 extruded polystyrene	none
W-2	1991/92	half-wall, interior R-10 extruded polystyrene	none
W-3	1993/94	full-wall, interior R-8 molded polystyrene	none
W-4	1994/95, 1995/96	full-wall, interior R-11 fiberglass batts in wood stud frame	interior 4-mil. polyethylene membrane beneath frame
W-5	1996/97	full-wall, interior R-14 polyisocyanurate foam	foil facing on both sides of polyisocyanurate foam
W-6	1998/99	full-wall, interior, R-10 semi-rigid fiberglass board	mixed: none over 50% of the wall surface; interior 6-mil. polyethylene membrane over 25% of the wall surface; wall/insulation interface 6-mil. polyethylene membrane over 25% of the wall surface.

strictly thermal transport perspective, the location of the insulation (whether interior, exterior, or mid-wall) yields the same performance within the experimental error. Thus from an energy sustainability perspective, there is no benefit to increasing the continuous insulation thermal resistance beyond a R_{US}-value of 8 given a constant insulation thickness over the entire wall surface in a Minneapolis climate. This is depicted in Figure 5 showing the simulated energy performance of a full basement foundation in a Minneapolis climate as a function of wall insulation thermal resistance (the floor is uninsulated).

Figure 5 reveals that there is a significant energy savings for the first R_{US}-5 of insulation with the gradient of the normalized heat flow declining thereafter. The gradients of the experimental normalized envelope heat flows that are shown in the short curves towards the bottom right of the figure define the uncertainty bounds of the experimental data between which the simulated profile gradient for R_{US}-values greater than about 8.5 neatly falls. Thus these error bounds are used to define the "optimization band" for foundation wall insulation that captures the experimental uncertainty.

Additional calculation extended this result over all of Minnesota (Goldberg and Huelman 2005) with the consequence that the Minnesota energy code foundation rule requires R_{US}-10 as the minimum level of foundation insulation in Minnesota without the invocation of a furnace efficiency "trade-off" in the southern half of the state (in which case, exterior R_{US}-5 insulation is permitted). This trade-off, that has no physical justification and was not recommended, is an example of how politics intrudes into the building code writing process, often to the detriment of sustainability.

Thus improving the energy performance of foundation envelopes is not obvious; indeed, it has transpired that first law thermal analysis (that is, the first law of thermodynamics) is not adequate to the task. Invoking a second law or entropic analysis does provide some clues because it allows a visualization of where the largest entropy generation rates in the foundation occur, and hence the greatest source of irreversibilities. This type of analysis reveals that ideally a continuously varying thickness of insulation both vertically (decreasing from the wall top downwards) and horizontally (decreasing from an exterior corner inwards) can improve the conduction energy performance of the wall. This, however, is unlikely to be implemented in practice in standard construction owing to the higher labor costs of its installation. However, it is not impossible and can be implemented with spray applied insulation that permits very precise control of the deposited thickness.

However, while there is not much impact on the thermal performance, insulation type can have a profound impact on the moisture transport performance of foundation systems as shown in Figure 6 and Table 1.

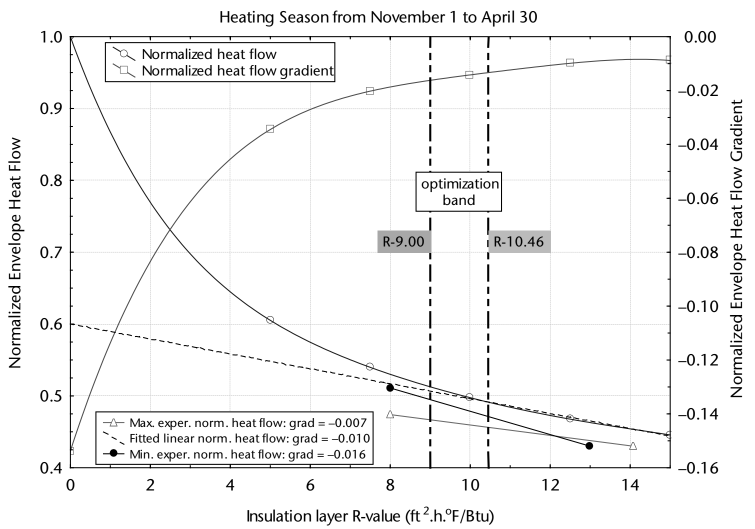


FIGURE 5. Minneapolis full basement foundation wall system insulation layer optimization.

Figure 6 reveals some of the perhaps counter-intuitive impacts of various foundation insulation and vapor retarder configurations on the overall foundation envelope moisture transport. These data show the amount of condensate removed from the west basement module under constant, continuous dehumidification rate conditions. Again, the data are normalized against those of the north reference module, and it must be emphasized that only the vapor retarders described in Table 2 were included, so that, for example, there were no floor vapor retarders in any of the systems shown in Figures 4 and 6.

The key aspect of Figure 6 is that 2 in. of 15psi extruded polystyrene with a nominal permeance of 0.55 US perms yielded by far the lowest overall envelope vapor transport, less than half that of system W-4 with a full-wall interior polyethylene membrane between the stud frame and the wall surface (nominal permeance of 0.08 US perms). This initially very surprising result (replicated over a two-season test period) provided one of the early indicators of the vapor transport performance advantages offered by semi-permeable insulation systems. In these systems, the overall desired permeance (traditionally 0.1 to 1 US-perm for warm-side vapor retarders) is diffused over the thickness and yields a moisture transport mechanism akin to electron (or "electron hole") tunneling in semi-conductors. Thus, each water molecule tunnels its way through a tortuous path in the insulation so that until the tunnel is full, the insulation acts as a moisture store. If the relative humidity (RH) on the source side varies with time so that it oscillates about the mean RH within the insulation, the moisture front within the insulation will move inwards and outwards, and, if the insulation is thick enough, never penetrate all the way through. If the source humidity is fairly constant and is always higher than that in the insulation, the front will move all the way through the insulation so that a molecule entering on the source side of the tunnel will displace a molecule on the sink side. This occurs on the below-grade portion of foundation walls. The tunnel-through period was observed at the FTF to be very approximately two years for interior extruded polystyrene insulation and 6 months for interior expanded polystyrene. Once the tunnels are full, the observed permeance of the insulation system increases to levels similar to those shown for the other systems in Figure 6.

These results provide a highly circumscribed snapshot of foundation system phenomenology just from energy and vapor transport perspectives with a view to illustrating the complexities of the foundation design problem. Similar complexities can be found with regard to the impact of frost on the structural performance of the foundation system, as well as the consequences of radon mitigation techniques

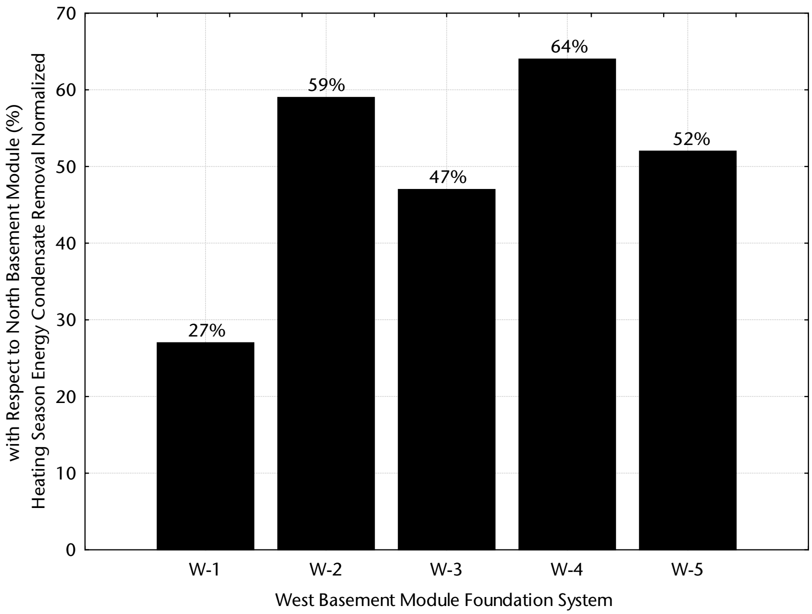


FIGURE 6. West basement module combined heating season condensate removal under continuous, constant rate dehumidification conditions.

such as sub-slab depressurization. These complexities are magnified in the context of sustainable design both in terms of achieving further energy savings as well as in using materials that can be recycled and are not based on fossil fuel raw material inputs.

FOUNDATION REQUIREMENTS

Within the framework established by the research results, the following requirements for designing a sustainable foundation system within the constraints established by economic viability can be delineated:

- Provide a water separation plane between the soil and the interior.
- Resist the transport of water vapor across the foundation envelope to reduce latent energy loads (dehumidification costs).
- Provide a thermal barrier between the soil and ambient surroundings to minimize sensible energy loads (heating and cooling costs).
- Provide adequate structural support in the presence of below-grade freezing temperatures, frost-susceptible soils, and high moisture contents.
- Reduce radon ingression to levels consistent with relevant building codes (typically 4 picoCuries per liter or less).
- Yield a thermally comfortable basement space free of odors and high or low humidity extremes.
- Ensure that the foundation envelope is durable for the economic life of the building (nominally 100 years) and specifically that it will not fail as a result of biotic activity (mold, rot, and infestation) from the interior or exterior.
- Use building materials that are maximally sustainable within the constraints imposed by the other requirements.

These requirements are universal; they apply to all foundations types (full basement, crawl space, slab-on-grade, grade-beam, etc.) in all climates as long as there is a direct interface between the ground and the building interior.

DESIGN PERFORMANCE SPECIFICATION

Foundation design meeting the requirements listed above can most effectively be accomplished by using a physics-based approach centered on a set of performance requirements and criteria rather than the more traditional building code prescriptive approach. This approach does not constrain the designer to any particular configuration or set of materials, but simply delineates the performance standards that the foundation system must meet. This concept is included in the draft Minnesota residential building code rule (Chapter 1322, section N1102.2.5.5, dated 7/17/2006) that is based on a research report prepared by the University of Minnesota (Goldberg and Huelman 2005). Generalizing the research report criteria to be universally applicable yields the following:

A. Definitions

Foundation: A foundation comprises a floor system and an exterior perimeter wall system in contact with the earth.

Foundation wall system: A continuous and homogeneous vertical structural system, a portion of which must be in contact with the earth.

Foundation floor system: A continuous and homogeneous horizontal structural or non-structural system in contact with the earth.

Water separation plane: A single component or a system of components creating a plane that prevents capillary water flow and water flow caused by hydrostatic pressure and provides a water vapor permeance of 0.1 US perms or less to retard water vapor flow by diffusion.

Foundation insulation layer: A system of building materials connected in series and/or in parallel excluding surface heat transfer film coefficients that serves as thermal insulation in foundation wall and floor systems.

Foundation air barrier system: A material or combination of materials that has the following characteristics:

1. It is continuous with all joints sealed.
2. It is durable.
3. It resists the transport of an air/water vapor mixture as a result of an exterior-interior pressure difference to the minimum extent necessary to achieve moisture durability and a given level of energy efficiency.

Stable annual wetting/drying cycle: A water (solid, liquid, and vapor) transport process operating on a foundation that produces no net accumulation of ice or water over a full calendar year and is free of adsorbed water for at least four months over a full calendar year.

B. Design Requirements

A building foundation shall be designed to meet the following requirements:

1. Have a continuous water separation plane between the exterior and interior.
2. Not allow external liquid water intrusion (including capillary flow) across the water separation plane after the foundation is backfilled.
3. Have a foundation wall system insulating layer with an equivalent continuous, uniform thermal resistance without any thermal breaks that just yields the envelope heat flow/thermal resistance profile minimum linear regression fitted gradient (that is, per Figure 5).
4. Have a foundation air barrier system between the interior and the exterior.
5. Prevent structural damage produced by frost heave or adfreezing.
6. Prevent structural or insulation system damage by animal or insect infestation.
7. Provide a continuously operating sub-slab depressurization system that maintains foundation interior radon levels at prescribed health standards.

C. Design Criterion

On the interior side of the water separation plane, a building foundation system shall be designed to have:*

1. A stable annual wetting/drying cycle.
2. No visible or olfactory fungal or other biotic activity.
3. No bulk water movement.

****Exceptions***

Bulk water movement (such as condensate rundown) is allowed on the interior side of the water separation plane under the following conditions:

i. There is no accumulation of free water on the interior side of the water separation plane *and* the above-grade portion of the foundation wall system does not exceed 17% of the foundation wall system height, or,

ii. There are components of the foundation wall system inside the water separation plane designed specifically to absorb and store moisture so that there is no accumulation of free water on the interior side of the water separation plane when at least 63% of the foundation wall system height is above-grade.

The definition of the water separation plane (WSP) is such that in practice it can only be realized by a "waterproofing" system. The original report (Goldberg and Huelman 2005) referred to a "bulk" water separation plane without the specification of a maximum permeance of approximately 0.1 US perms in the definition. The definition was changed during the rule writing process for simplification and clarification purposes and to reflect the reality that effective waterproofing systems generally have permeances less than 0.1 US perms. The foundation insulation layer is defined to exclude surface heat transfer coefficients and its application to the defined foundation wall and floor systems ensures that the resistance of the encapsulating earth is excluded from the calculation. The concept behind this is to require the usage of optimum levels of foundation insulation within the context of an earth-contact environment and not detract from the energy sustainability of the foundation by discounting insulation R-value against that provided by the surrounding earth.

The definition of the foundation air barrier system is designed to maximize design flexibility and, in particular, the use of sustainable building materials. Hence, for a particular foundation system that meets the requirements and criterion, it is possible to quantify the maximum amount of air leakage permissible for that particular system in terms of moisture durability and energy efficiency (typically specified as an envelope infiltration rate). From an energy perspective alone, however, it theoretically always is desirable to minimize infiltration and hence maximize the advective resistance of the air barrier. Thus the quantitative minimum performance of the air barrier in any particular design is a function of the system and imposed boundary conditions and can be determined by standardized testing of that design. The minimum performance can be expressed in terms of an air permeability requirement as follows: "The foundation air barrier system shall have an air permeability not to exceed x $ft^3/min.ft^2$ ($l/s.m^2$) at a pressure differential of y psf (Pa) when tested in accordance with ASTM E2178."

The wetting/drying cycle stability is defined in terms of adsorbed (or surface attached) water, since that is what is significant in the development of foundation system mold and rot that typically are initiated on the surface. The moisture content required to achieve a stable annual wetting/drying cycle for the materials in a particular design is a function of the specific materials used, the system, and the boundary conditions. For example, above-grade testing at the Cloquet Residential Research Facility (Goldberg, Huelman and Ober 2001) has shown that a stable annual wetting/drying cycle can be realized with gravimetric moisture contents for particular materials sampled in June as follows:

- cellulose: 12.3–15.7%
- blown-in blanket system (BIBS): 1.3–2.6%
- fiberglass batt: 2.0–3.0%
- wood stud: 6.0–10.3%

Thus, provided a particular material does not exceed its bound water carrying capacity (much higher for hygrophilic materials such as cellulose, much less for hygrophobic materials such as BIBS), and has no adsorbed water for at least four months in a calendar year, it is sufficiently dry for achieving annual wetting/drying cycle stability.

It is important to note that the WSP requirements 1 and 2 apply to both the foundation wall and floor systems. The requirement that the WSP be fully functional after the foundation is backfilled is intended to eliminate the abuses typical of average construction practice in which whatever is excavated is simply pushed back into the hole including rocks, clumps of frozen soil, and other materials that can damage the exterior waterproofing and/or insulation. This also applies beneath the slab where the typically used 6-mil. polyethylene membrane is more or less rendered useless by damage during the construction process, often by careless perforation for the installation of plumbing and electrical utilities. These perforations usually are not resealed prior to the pouring of the slab. In addition, 6-mil. polyethylene is not durable enough to withstand the mechanical abuse of the pouring process so the requirements necessitate the use of more durable materials (such as membranes with cross-linked reinforcement).

The equivalent continuous uniform R-value of discontinuous foundation insulation layers (such as fiberglass batts in wood framing) needs to be calculated. A standard method for performing such a calculation is described in the ASHRAE *Handbook of Fundamentals* and referred to as the "method of isothermal planes." However, this basic, 1-dimensional heat flow methodology does not produce an accurate R-value for installed framed wall foundation insulation layers in particular and tends to overestimate the R-value. Hence, a better approach is to use a steady-state, 3-dimensional finite element analysis computer simulation.

Currently, the best method of calculating the design R-value referred to in requirement 3 for any climate, soil type, and foundation geometry is to use 3-dimensional, thermal conduction computer simulation with temperature dependent material properties. With reference to Figure 5, the simulation is used to generate the net foundation envelope (that is, walls and slab) heat flow as a function of insulation thermal resistance over a climate appropriate range for the relevant heating season duration. A smooth curve is fitted to these data (such as a fifth order polynomial) and the resulting equation used to generate the heat flow gradient profile. By progressively fitting a least squares straight line to the plotted points from the right hand side of the heat flow profile backwards, the point at which significant deviation from the fitted straight line begins defines the optimum R-value. Ideally this should be based on an annual transient calculation (as is the case for Figure 5); however, generating the heat flow profile using winter steady-state "design day" calculations is not an unreasonable approach. There are many commercial finite element simulation programs that can be adapted for this purpose (especially for steady-state calculations).

Requirement 3 also stipulates that the foundation insulation system not have any thermal breaks or short circuits. These are defined as direct heat flow paths between the exterior and interior that bypass the insulation layer. This is intended to encourage the use of homogeneous insulation systems (such as spray-applied foam or continuous rigid insulation) that also eliminate the need for a thermal resistance calculation. It also excludes poor insulation practices such as those that can occur with slab-on-grade/stem wall foundations with interior insulation. Very often in such systems, the foundation slab is poured on a lip set in to the interior top of the stem wall. Insulation is placed on the interior of the stem wall up to the bottom of the lip and on the vertical portion of the lip leaving a massive thermal break on the horizontal lip surface. Continuous insulation in this application can readily be achieved using exterior, integral (or mid-wall) insulation placement or alternate construction methods such as insulated concrete forms.

The remaining requirements are self-explanatory, although some comment on the implications of requirement 5 is warranted. Frost heave can be avoided by eliminating just one of the three prerequisites for its occurrence, namely, freezing temperatures, frost susceptible soils, and an adequate bulk water source (such as a high water table). Most cold climate building codes stipulate a minimum footing depth below which the frost supposedly does not penetrate. However, experience has shown that very often these footing depths are inadequate because they are calculated or measured with unrealistic or optimistic boundary conditions. Typical of such conditions is the assumption of an average snow cover depth that provides a substantial insulating blanket between the ambient surroundings and the soil. With the advent of global increases in average ambient temperature (Hansen, Ruedy, *et al.*, 2005*)*, such average snow depth assumptions are not warranted, and thus the footing depth needs to be increased to accommodate this. Ideally, the footing depth should be calculated or measured with zero snow cover (typically the case for the design of frost-protected shallow foundations); however, this can yield quite large footing depths requiring expensive excavation. A better approach is to still require current code specified footing depths but add the requirement for the installation of adequate drainage around the footings so that the sub-slab footing region is deprived of an adequate bulk water source. This is particularly relevant to slab-on-grade/stem-wall foundation systems for which the *International Residential Code* (for example) does not require a drainage system.

The design criterion is the core of the performance design methodology, and here, "criterion" is used in terms of its strict definition as a "principle taken as a standard in judging." Because of the complexity of heat and mass transfer in foundation envelopes, it is not practical to cast the desired moisture performance as a requirement because no matter how sophisticated the design analysis, ultimately, the only credible test for compliance is the long-term experimental evaluation of full-scale prototypes. However, when used as a criterion, the described moisture performance has proved to be very effective in yielding designs that have displayed the desired physics without exception upon being tested. After the systems have been tested and proved successful, then specific quantitative moisture performance requirements based on standard test procedures for that particular system can be developed and stipulated as design requirements.

The development of a criterion for avoiding mold and rot in a foundation system proved to be very challenging. Currently, the apparent consensus amongst the fungal testing community is that there are no efficacious standard test procedures currently available for determining the *a-priori* fungal performance of a foundation "system." There are guidelines for fungal sampling of built building components, but these are invasive and are based on culturing retrieved samples. Further, these tests also are subjective to a degree since they involve establishing a cultured species "colony forming units/unit area" (or equivalent) count pass/fail criterion that is related to human macro detection based on sight and smell. Thus, despite its subjectivity, a "no see, no smell" fungal activity evaluation has proved to be a practical and effective means for establishing the fungal performance of foundation systems and has been used as a standard in developing successful foundation insulation systems at the Foundation Test Facility to the satisfaction of the research sponsors. The draft Minnesota foundation rule takes a less direct approach and states that the foundation shall be deigned and built to "*Prevent conditions of moisture and temperature to prevail for a time period favorable to mold growth for the materials used"* on the interior side of the water separation plane (section N1102.2.5.5.1).

SOME EXAMPLES

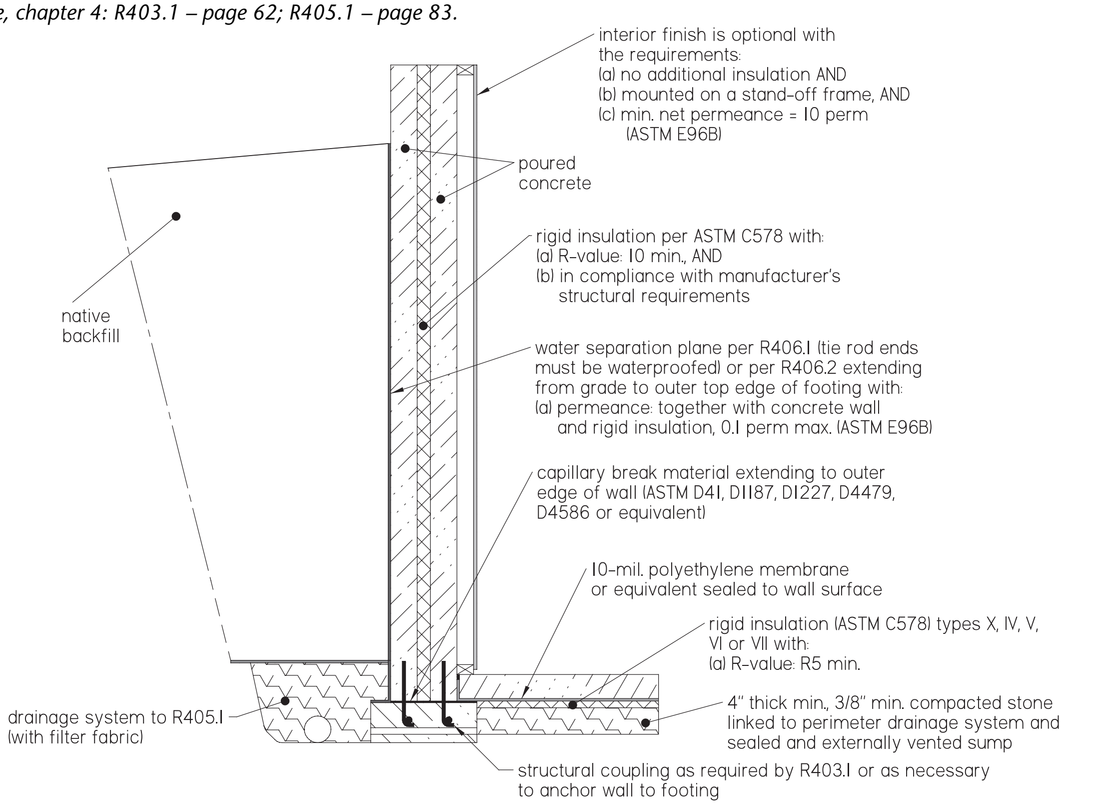
The following examples of foundation systems fully meet the design performance specification and are illustrative of the very broad range of designs that are possible. The references to N1102.2.6.1 in Figures 8 and 9 refer to the following language in the 7/17/06 draft of Chapter 1322 of the Minnesota Rules:

> *"**Protection of exposed foundation insulation.** Insulation applied to the exterior of foundation walls, crawl space walls and the perimeter of slab-on-grade floors shall have a rigid, opaque and weather-resistant protective covering to pre-*

vent the degradation of the insulation. The protective covering shall cover the exposed exterior insulation and extend a minimum of 6 inches (153 mm) below grade. The insulation shall be a water resistant material, manufactured for its intended use, and installed according to the manufacturer's specifications."

Figure 7 depicts perhaps one of the most robust residential full basement foundation insulation systems with universal applicability; however, the thermal resistances of the uniform thickness insulation shown have been optimized for a Minnesota climate. The exterior water separation plane (WSP) extends continuously from grade, down the exterior wall, across the top of the footing, and beneath the slab. The WSP is extended above grade by the wall structure itself (two layers of concrete and R_{US}-10 extruded polystyrene) that is adequate for the prevailing bulk water and water vapor boundary conditions there. Purists would argue that the WSP should be extended above-grade as well. However, it is not strictly necessary, and its exclusion eliminates the need for protecting the above-grade portion against UV radiation if required by the WSP specification. The exterior concrete layer resists infestation by insects, rodents, etc., and also protects the insulation against structural damage. The exterior drain tile system combined with the depth of the footing prevents frost heave while the WSP provides a slip-sheet to resist adfreeze frost damage. Sub-slab R-5 insulation beneath the 10-mil. polyethylene membrane (forming the sub-slab WSP) provides a warm slab interior surface thereby avoiding the common problem of surface condensation during the cooling season. The sub-slab compacted stone layer is connected to the exterior drainage system through a port in the footing, and the entire drainage system is linked to a sealed and vented sump. This provides the sub-slab radon mitigation depressurization system that intercepts soil gas (including radon and water vapor) both from beneath the slab as well as from the exterior wall perimeter. Because the WSP extends across the top of the footing, a structural connection is neces-

FIGURE 7. Full basement integral insulation. *The following are references to sections in the 2003 International Residential Code, chapter 4: R403.1 – page 62; R405.1 – page 83.*

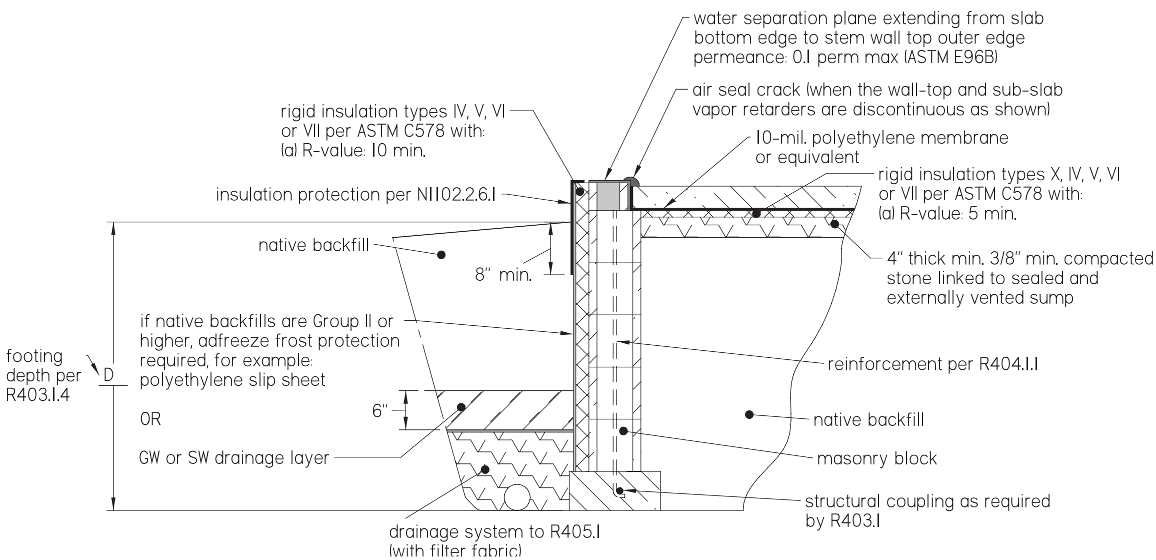


sary between the footing and the wall to prevent lateral movement of the wall and this is provided by the reinforcing rods. No warm-side (or interior) vapor retarders are required with this configuration and hence any interior finish is optional. Any such finish must have a permeance of at least 10 US perms in order to allow unrestricted drying of any incidental water leakage to the interior. The air barrier between the interior and exterior is provided by the structural wall system itself. Note that the combination of the encapsulating WSP as well as the sub-slab depressurization minimizes (if not substantially eliminates) soil water vapor ingression to the basement, and in so doing reduces latent loads very substantially. This can produce very significant energy savings in mixed climates where basements are prevalent, particularly as summer humidity levels increase with the changing global climate.

Figure 8 shows a more conventional application to a stem wall/slab-on-grade foundation (again optimized for MN climate conditions). Note that the exterior drainage system has been augmented by an additional 6" drainage layer. This layer is intended as a filtration mechanism to prevent the filter fabric from becoming clogged with fines over an extended period, a circumstance that compromises the ability of the drainage system to keep the footing region free of frost. In this case, even though not mandated by code, the external drainage layer provides the frost heave protection system as the MN code required footing depth is insufficient to prevent frost intrusion at external corners (even with exterior insulation) under all conditions (such as minimal snow cover). The WSP is continuous from the exterior edge of the top of the wall, through the slab lip and beneath the slab. The sub-slab system is the same as that for the full basement system described above. Note that sumps are not typical in slab-on-grade construction, particularly for the purpose of dewatering the footing drainage system owing to their depth beneath the slab. Hence it is preferable, if possible, to drain the footings to daylight since a shallow sump only is necessary for sub-slab depressurization. The exterior insulation requires a polyethylene slip sheet or equivalent adfreeze frost protection, and the exposed insulation requires above-grade protection from UV radiation. Note that the entire stem wall system is on the exterior side of the WSP, so no below-grade waterproofing is necessary.

Finally, Figure 9 depicts a more complex permanent wood foundation applied to a crawl space with the interior grade above the level of the footing. The WSP extends from the top of the exterior plywood sheathing down across the top of the bottom plate

FIGURE 8. Slab-on-grade/frost footing stem wall exterior insulation system. *The following are references to sections in the 2003 International Residential Code, chapter 4: R403.1 – page 62; R403.1.4 – page 63; R404.1.1 – page 72; R405.1 – page 83.*



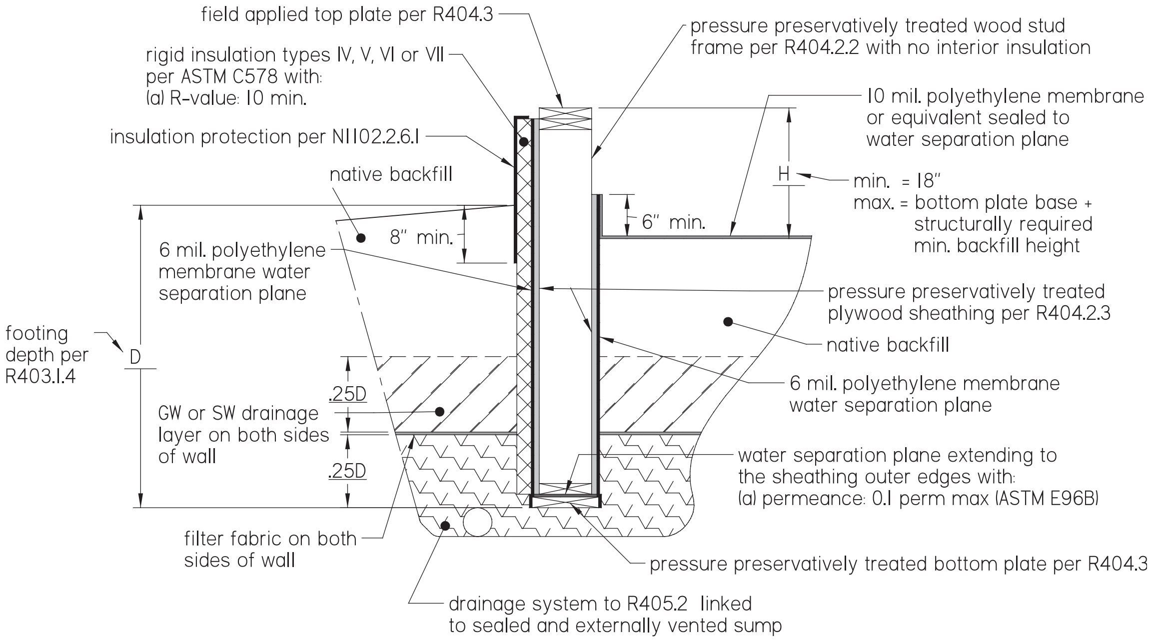


FIGURE 9. Externally unvented crawl space permanent wood foundation. *The following are references to sections in the 2003 International Residential Code, chapter 4: R403.1.4 – page 63; R404.2.2, R404.2.,3 R404.3 – page 77; R405.2 – page 83.*

and then up the interior plywood where it is sealed to the 10-mil. polyethylene floor membrane. This creates vapor sealed frame wall pockets that are open to the interior allowing any incidental leakage to readily dry out. Because of the elevated level of well-draining soils on the exterior, an adfreeze protection slip sheet is not necessary in this case.

SUMMARY AND CONCLUSION

Residential building foundation systems are the basis for sustainable building design. The complexity of their hygrothermal transport phenomenology combined with the imposed structural requirements make sustainable foundation design very challenging. A research basis overview that was used to develop a generalized performance-based approach to foundation design has been described and the resulting design performance specification discussed in terms of its universal applicability. Examples of various foundation designs illustrating the application of the design methodology have been given.

The described approach to designing durable and energy efficient foundations provides the basis on which sustainable residential buildings can be constructed. It is expected that residential buildings built according to these principles and combined with other deep conservation technologies will achieve at least calendar year net zero energy operation even in cold climates. Building physics research in Minnesota and elsewhere now is focused on using these concepts to make net zero energy houses the norm, both in practice and by regulation.

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