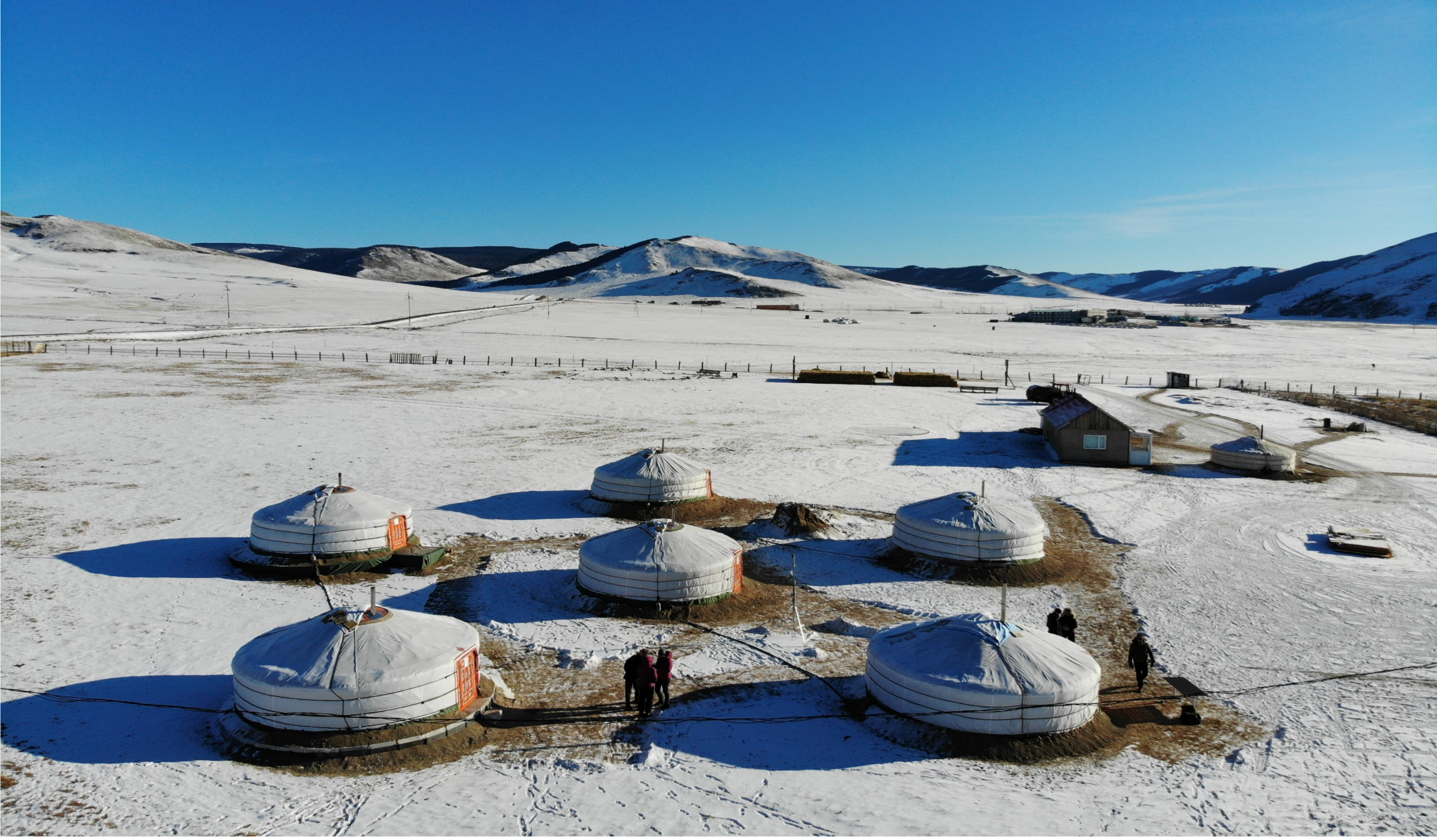
CENTER FOR ENVIRONMENTAL BUILDING AND DESIGN

Designing the 21st Century Ger

Monitoring and Diagnostics 2018-19



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Executive Summary

In the winter of 2018-19, the thermal behavior of twelve Mongolian ger were studied in detail: five Occupied Ger in Ulaanbaatar, six Test Ger at a "ger ranch" outside the city, and one highly instrumented Penn Ger at the University of Pennsylvania in Philadelphia. The study was conducted in support of programs by UNICEF and Ger Hub to reduce or eliminate coal consumption in the ger district. The ultimate goal is a "21st Century Ger" that can be operated affordably without a central stove, heated with electricity or other thermal sources.

<u>The principal result was that an improved, better insulated ger can be heated affordably with electricity.</u>

The research set out to evaluate the different pathways of heat loss in ger and to identify techniques for reducing those losses. There are five pathways by which ger lose heat: (1) the wall/roof, (2) the door, (3) the toono, (4) the floor, and (5) by air infiltration through leaks and cracks. To reduce energy use each of the pathways must be reduced proportionally. Dramatically improving one aspect—adding many additional layers of felt for example—loses its value after the first additional layer, because heat is still flowing through the other pathways (in a leaky roof, you have to patch all the holes). The specific results for each pathway of heat loss are as follows.

1. **Wall/Roof.** Adding additional layers of insulation to the wall and roof makes a significant difference because the areas are so large. Each additional layer can reduce heat loss by 10-20% (in balance with other improvements). It can also help to add an additional vapor/wind barrier to resist the penetration of wind, though care must be taken to manage the condensation of water vapor. Ger E had three layers of felt in the walls and roof. An additional benefit can be obtained by using a darker colored exterior cover to absorb more sunlight, offsetting some of the heat losses.
2. **Door.** Adding a layer of insulation to the door makes a meaningful reduction in heat loss, and weather stripping the gaps reduces air infiltration. The research could not separate the effect of the door insulation its impact on infiltration or its interaction with the toono cover (see below), but in the Occupied ger it reduced stove firings from three times a day to two.
3. **Toono.** Adding a more insulated toono cover reduced heat loss by up to 25%, both by insulating the toono itself and reducing air infiltration. The design of an insulated toono cover will be greatly simplified if it does not have to accommodate a flue pipe.
4. **Floor.** Adding insulation to the floor reduces heat loss to the ground and increases the surface temperature of the floor, making the ger more comfortable. This will be more important in an all-electric ger without the concentrated heat of the stove. It is especially important to develop a better insulation detail for the joint between the wall and floor.
5. **Air Infiltration.** Eliminating the coal stove and chimney cut air infiltration by half and can reduce overall heat loss by 10-25%. The study was not able to examine the effect of a vestibule, but research on similar forms of construction suggest that a well-sealed vestibule can reduce the infiltration associated with regular opening of the door.

In general, Ger E, the "everything ger," provides a model for a low-cost, 21st Century Ger. However there are many regional and individual differences in ger construction, so improvements don't have to follow the exact formula used in ger E, as long as the insulating properties are improved in each of the five pathways.

Introduction

With the steady urbanization of Mongolia since the 1960s, former nomads have been settled in legal, semi-formal "ger districts" at the perimeter of the capital city, Ulaanbaatar. Roughly 60% of the residents of the capital live in a combination of ger (Yurt in Russian) and self-built rigid frame houses, which burn soft coal to keep their dwellings warm, making it one of the most polluted cities in the world. The Penn project supports initiatives by UNICEF and Ger Hub to reduce or eliminate the combustion of coal by improving the thermal efficiency of ger. In the winter of 2018-19, the thermal behavior of twelve Mongolia ger were studied in detail: five Occupied Ger in Ulaanbaatar, six Test Ger at a "ger ranch" outside the city, and one highly instrumented Penn Ger at the University of Pennsylvania.

For coal-heated ger there is no easy way to compare their thermal performance or, more importantly, to evaluate the effect of improvements. The first year of the research (2017-18) was devoted to developing audit and diagnostic protocols to evaluate coal-heated ger. The team imported and assembled a Mongolian ger at Pennovation, the research campus of the University of Pennsylvania, monitoring it to understand its thermal behavior and to identify opportunities to improve its comfort and energy performance. For this second year, we collaborated with teams from Kieran Timberlake, North Face, and Arc'teryx, on a discrete set of improvement for testing at the ger-ranch.

The results will support efforts to reduce or eliminate coal consumption in the ger district and to provide the basis for an auditing protocol or "ger-doctor" program. The ultimate goal is a "21st Century Ger," a ger that can be operated affordably without a central stove, heated with electricity or other thermal sources.

Research Goals

The research goals for the project can be divided into three categories.

- **AUDIT.** Deploy sensors of different kinds to monitor all the ways that heat moves through the ger and test auditing techniques that could be used in a "ger-doctor program."
- **ANALYSIS.** Use audit data to identify the pathways of heat loss and to evaluate strategies for reducing energy use and enhancing comfort
- **21st CENTURY GER**. Use research results to describe the components of a high-performance ger that can be heated with electricity or other low-pollution, low-carbon sources of heat.

Audit

The auditing of the first year focused on techniques for evaluating ger with coal-stoves, which were applied in the second year to the five occupied ger in the ger district, however the ger at the ger-ranch were heated much of the time with electric heaters, which simplified some of the analysis and also provided testing for future all-electric ger.

- Continuous Monitoring: All twelve ger were equipped with continuous recording of temperatures, humidity, CO2 levels, and other parameters to evaluate thermal behavior of ger and analyze the effect of improvements in the test ger.
- Benchmark Audit: A variety of techniques for discrete benchmark audits were tested in the Penn Ger in Philadelphia, including cool-down tests, constant electric heating tests, infrared thermography, and two forms of air infiltration tests, one with CO2 and one using a humidifier.

Analysis

There were five general questions the analysis was used to answer.

- Comparative evaluations among the 6 improved prototypes at the ger ranch
- Thermal load analysis to evaluate the relative importance of different pathways of heat loss
- The infiltration rate of outdoor air, which is a significant source of heat loss
- The daily dynamics of moisture within the ger, which contributed to heat loss and degradation of the insulation and building envelope
- The thermal distribution of heat in the ground under the ger, which was a focus of three of the improved prototypes at the ger ranch and a factor in future all-electric heating schemes

21st Century Ger

In alignment with the general goal of reducing air pollution from coal stoves, the research identified the kinds of improvements needed to heat a ger with electric sources at a comparable cost to coal and wood heat. In general, Ger E, the "everything ger," provides a model for a low-cost, 21st Century Ger. However there are many regional and individual differences in ger construction, so improvements don't have to follow the exact formula used in ger E, as long as the insulating properties are improved in each of the five pathways.

Sites and Prototypes

There were three sites of investigation for the project, each of which was used to examine a different aspect of ger thermal performance. Figure 1

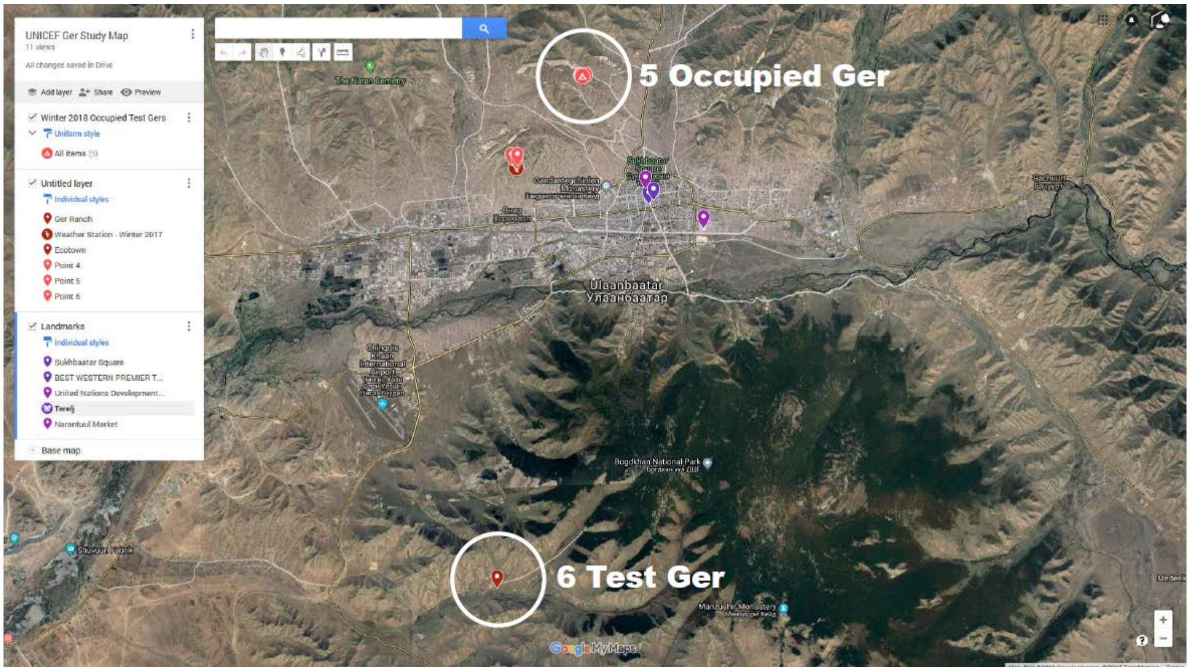

Figure 1. Location of occupied and test ger near Ulaanbaatar, Mongolia

- **Occupied Ger, Ger-District, Ulaanbaatar, Mongolia.**
  Five occupied ger in the ger district were monitored for temperature, humidity, and air quality, with the goal of better understanding the differences in operation and scheduling among different occupants. A weather station was installed nearby. Figure 3
- **Test Ger, "Ger Ranch," Ulaanbaatar, Mongolia.**
  Six ger were built on land near the city to evaluate the effect of individual improvements to standard ger construction. A weather station was also installed at the site. Figure 2 and cover photo
- **Penn Ger, Pennovation Research Campus, University of Pennsylvania, Philadelphia, PA.**
  One ger was built in Philadelphia with an insulated floor and a single layer of felt insulation. Because the climate has much more precipitation than Mongolia, an additional waterproof layer was added to the walls. Local temperature and solar insolation were measured on site and at a weather station located within a half mile. Figure 5

Figure 3. Occupied ger three and four, ger district

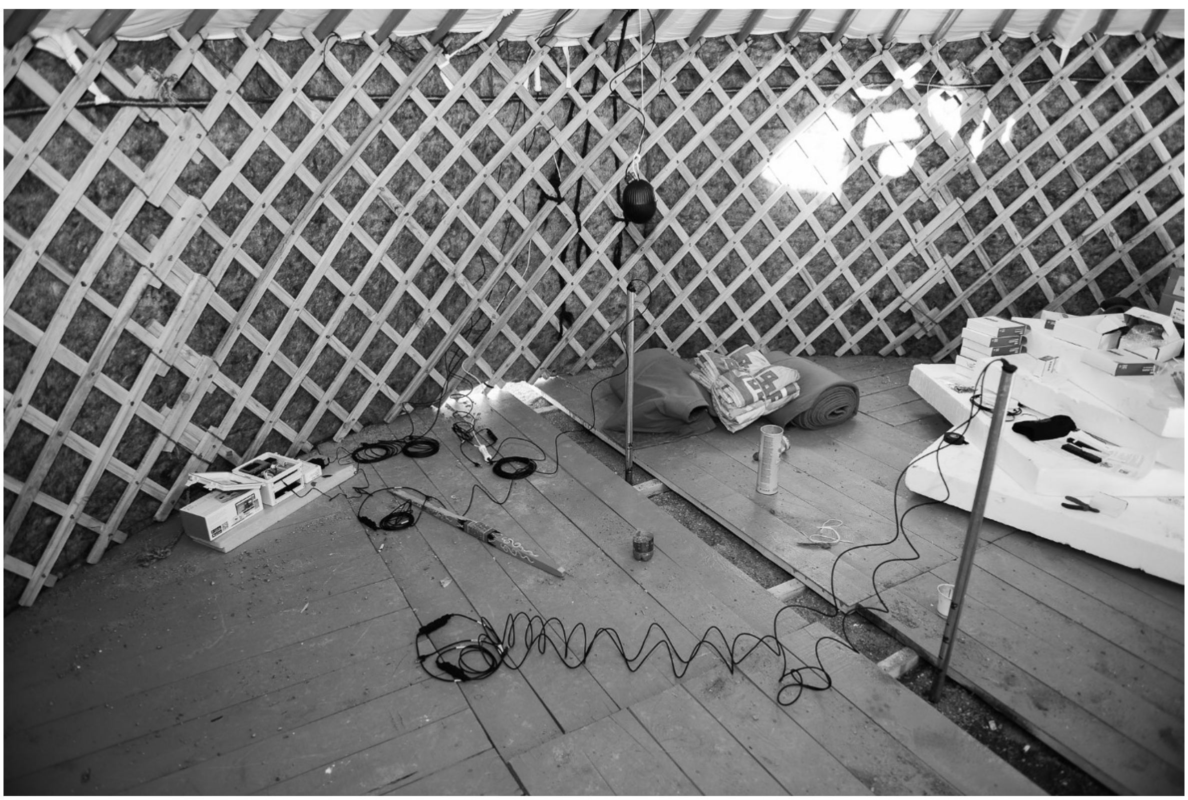

Figure 2. Installation of sensors and monitoring equipment, test ger

	
Ger A. Plain Ger.	*Ger B. Raised Floor*
	
Ger C. Mass on Grade	*Ger D. Insulated Door and Toono*
	
Ger E. Everything Ger.	*Ger F. Insulated Skirt*

Figure 4. Six Test Ger showing the floor edge details, especially exposed floor edge in B, C, and F

Figure 5. Penn Ger

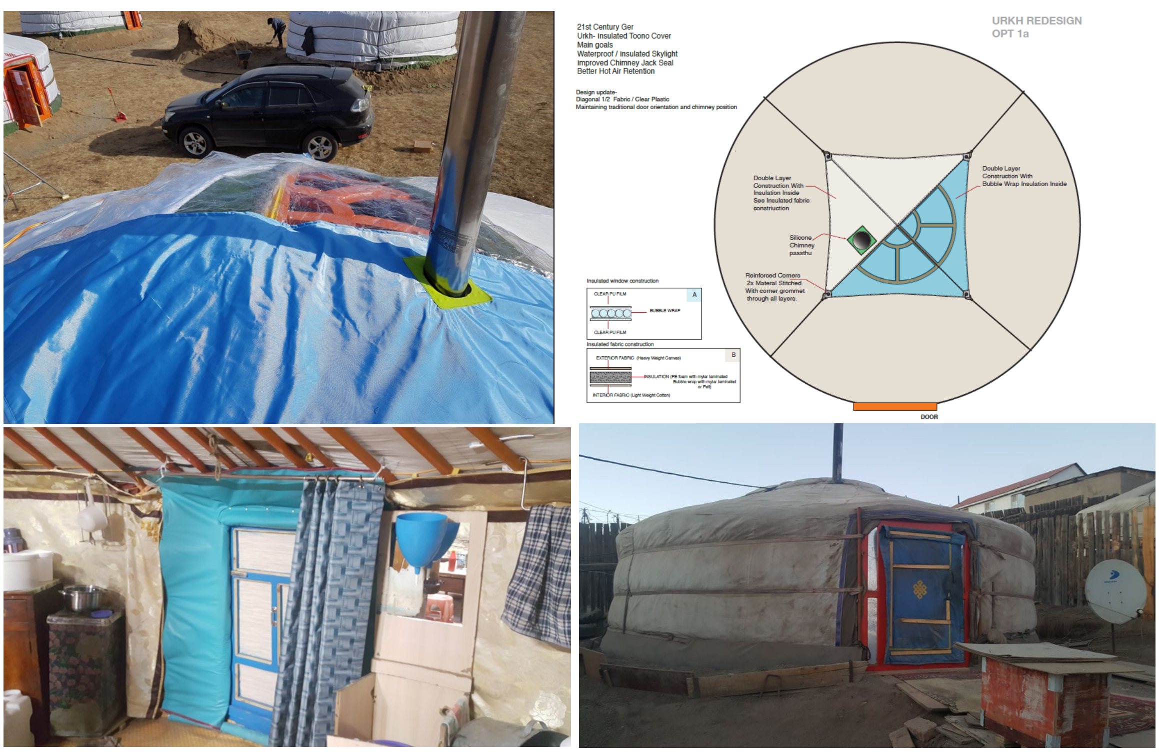

Figure 6. Toono cover (top) on ger D and door insulation (bottom) on occupied ger 4

Monitoring Protocols for Mongolian Ger

Ger are an elegantly simple form of construction developed for nomadic living in an extremely cold climate. Once heat is released inside, whether from a coal stove, electric appliances, or people themselves, there are only a few pathways for heat to get out of a ger, as illustrated in Figure 7. Heat can move into the ground through the floor, out through the fabric of the walls and ceiling, out through the wooden construction of the door and toono, or it can be carried by the outdoor air that infiltrates through cracks and holes.

The heat moving through floors, walls, ceilings, doors, and the toono can be reduced with better insulation, while the infiltration of air can be reduced by closing or sealing openings to the outside. The exhaust air from coal stoves further increases the rate of infiltration. Every bit of air used to carry smoke and pollutants up the chimney pipe pulls cold air in from the outside, so if the coal-stove is replaced with electricity or another source of heat, that directly reduces the infiltration of outside air.

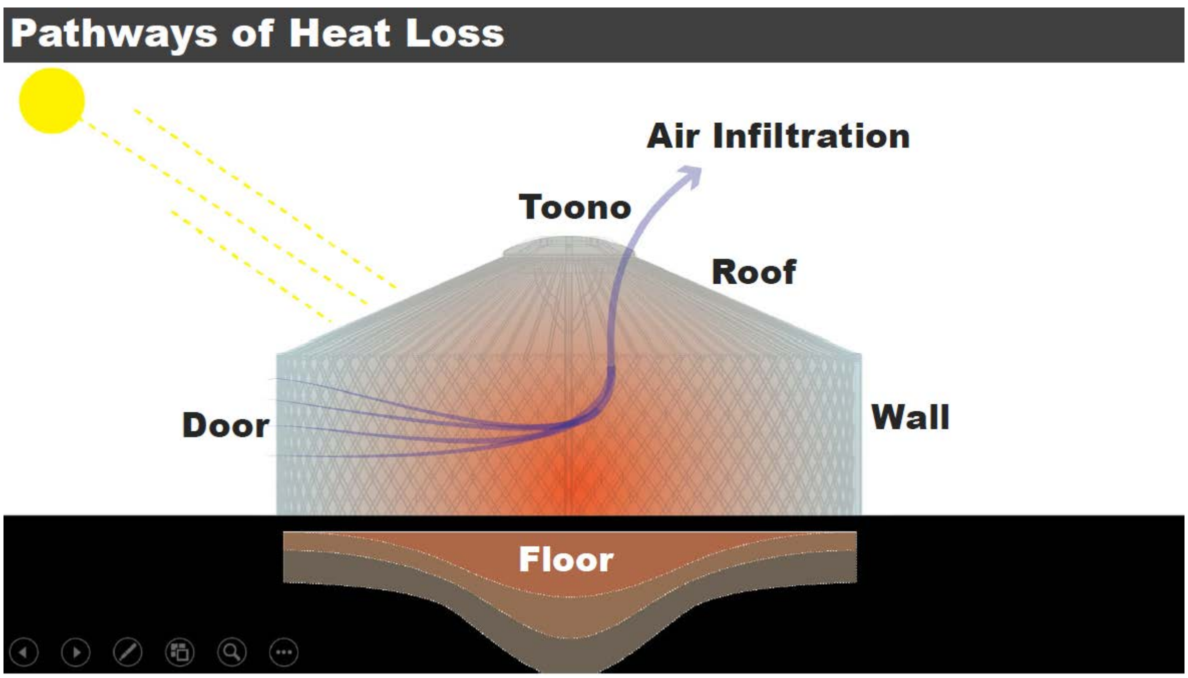

Figure 7. Five pathways of heat loss from Mongolian ger

Slightly different monitoring protocols were used for each of the testing sites, depending on their operation and the purpose of the monitoring.

Occupied Ger, Ger-District.

The occupied ger were all heated with coal stoves, so the amount of heat released by the stove was determined by monitoring the temperature of the stove and flue. Temperatures and humidity within the ger and the fabric of the walls were measured to evaluate the comfort of the space and heat flows. Ground temperatures below the ger were measured to determine how much heat was being lost to the ground. Two aspects of air quality were measure, CO_2 and PM2.5 particulates. The specific monitoring equipment and locations are detailed in Appendix A.

Test Ger, "Ger Ranch."
The six test ger built at the ger ranch were each planned to test a particular improvement or evaluate the importance of a specific pathway of heat loss. Their layout is indicated in Figure 8.

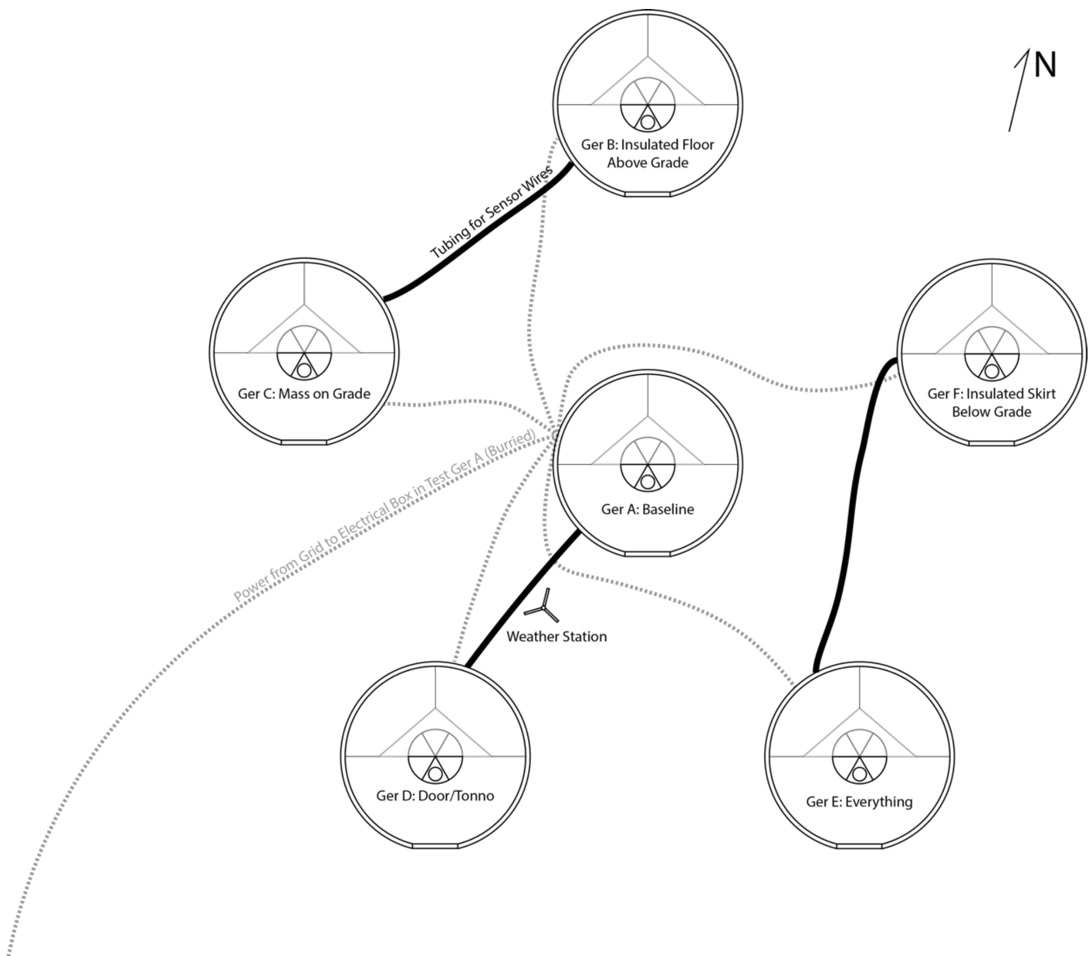

Figure 8. Location of six Test Ger at "ger ranch" outside Ulaanbaatar

- Ger A, the "plain ger," was an unimproved, standard 5-panel ger built on grade with a wood floor and a double layer of felt insulation. This was constructed to provide a reference for the other test cases.
- Ger B had an insulated floor raised off the ground. Raising the floor above a ventilated space is a preferred form for more permanent dwellings.
- Ger C had an insulated floor on grade with concrete tile flooring. Placing some massive material above the insulation can absorb and release heat, reducing temperature swings within the space.
- Ger D had an insulated door covering and an insulted toono covering. The door and toono are the least insulated portions of the ger exposed to outside air, so they are clear opportunities for improvement
- Ger E, the "everything ger," had an insulated floor, door, toono, and a third layer of wall and roof insulation. The everything ger was designed to determine if these simple improvements could reduce heating needs far enough to make an all-electric ger affordable.

- Ger F had an insulated skirt inserted vertically into the ground around the perimeter. Installing an insulated skirt could be the easiest way to retrofit existing ger and has the advantage of enclosing the dirt below the ger in the thermal envelope.

The six test ger all had an electric heater and a coal-stove, which were used in the schedule outlined in Table 1. The base heating was provided by electricity with designated weeks used to test the performance of the ger with coal. A number of other variations were also tested, including the removal of the door insulation (which was transferred to ger 4 of the occupied ger), the use of an outdoor air intake on the coal stove in ger B, and the use of humidifiers to perform a simple field test for infiltration rates.

Table 1. Testing schedule for the "Ger Ranch," showing periods of electric and coal heating and other variations

Oct - Jan	Test Ger		Wk-3	Wk-2	Wk-1	Week 1	Week 2	Week 3	Week 4	Wk 5A	Wk 5B	Wk 5C	Week 6	Week 7	Week 8	Week 9
			7-Jan	14-Jan	21-Jan	25-Jan-19	5-Feb-19	11-Feb	18-Feb	25-Feb	28-Feb	2-Mar	5-Mar	11-Mar	18-Mar	25-Mar
			13-Jan	20-Jan	24-Jan	4-Feb-19	10-Feb-19	17-Feb	24-Feb	27-Feb	1-Mar	4-Mar	10-Mar	17-Mar	24-Mar	28-Mar
26-Oct	**Ger A**	Fuel	Electric	Electric	Electric	Electric	Coal	Electric	Electric	Coal	Electric	Coal	Electric	Electric	Coal	Electric
Sensor	Baseline	Notes	3.5 k									Humidifier	Humidifier		Cool Down	Cool Down
Installation	"Plain"															
Nov - Dec	**Ger B**	Fuel	Electric	Electric	Electric	Electric	Coal	Electric	Electric	Coal	Electric	Coal	Electric	Electric	Coal	Electric
Testing &	Raised	Notes	3.5 k							Outdoor Air		Outdoor Air			Outdoor Air	
Adjustment	Floor											Humidifier	Humidifier		Cool Down	Cool Down
25-Dec	**Ger C**	Fuel	Electric	Electric	Electric	Electric	Coal	Electric	Electric	Coal	Electric	Coal	Electric	Electric	Coal	Electric
Extra Heaters	Mass on	Notes	3.5 k									Humidifier	Humidifier		Cool Down	Cool Down
	Grade															
	Ger D	Fuel	Electric	Electric	Electric	Electric	Coal - G Saver	Electric	Electric	Coal - G Saver	Electric	Coal - G Saver	Electric	Electric	Coal - G Saver	Electric
	Door	Notes	3.5 k					(2/16)				Humidifier	Humidifier		Cool Down	Cool Down
	/Toono		Dr/Tnno	Dr/Tnno	Dr/Tnno	Dr/Tnno	Dr/Tnno	Toono	Toono	Toono	Toono	Toono	Toono	Toono	Toono	Toono
	Ger E	Fuel	Electric	Electric	Electric	Electric	Electric	Electric	Electric	Electric	Electric	Coal	Electric	Electric	Coal	Electric
	Every	Notes	2k									Humidifier	Humidifier		Cool Down	Cool Down
	Thing															
	Ger F	Fuel	Electric	Electric	Electric	Electric	Coal	Electric	Electric	Coal	Electric	Coal	Electric	Electric	Coal	Electric
	Insulated	Notes	3.5 k									Humidifier	Humidifier		Cool Down	Cool Down
	Skirt															

Penn Ger.

The ger assembled at the University of Pennsylvania was equipped with the same basic package of sensors as the test ger, plus two additional arrays of Pointilist sensors, with up to 15 temperature and humidity sensors each. The arrays were used to map the distribution of heat under the floor and the distribution of heat within the air and the felt of the walls and roof.

The Penn Ger was mostly used to test protocols for evaluating air infiltration and for benchmarking tests for field audits of occupied ger. One week was used to heat the ger with coal and assess the difference in air infiltration. The full schedule of testing is outlined in Table 2.

Table 2. Testing schedule for the "Ger Ranch," showing periods of electric and coal heating and other variation

		Build	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 9
		13-Dec	21-Jan	26-Jan	3-Feb	10-Feb	17-Feb	24-Feb	5-Mar	10-Mar	17-Mar	24-Mar
			25-Jan	2-Feb	9-Feb	16-Feb	23-Feb	4-Mar	9-Mar	16-Mar	23-Mar	29-Mar
Penn	Fuel	Electric	Electric	Electric	Electric	Electric	Electric	Electric	Coal	Electric	Electric	Electric
Ger	Notes		Sensors	2/1 Cool Dn	2/8 CO2	2/14 Humid.	2/19 Humid.	2/26 Humid.	3/5 Humid.	3/12 CO2	3/17 CO2	3/27 CO2
			Installed		2/9 Cool Dn	2/15 Humid.	2/22 Humid.	3/2 Humid.	3/6 CO2		3/19 CO2	3/29 CO2
						2/16 Humid.			3/7 CO2		3/22 CO2	
									3/8 CO2			
									3/9 CO2			

Results and Analysis

1. Comparison of Prototypes

A direct comparison of energy usage among the six test ger is possible because they were heated most of the time with electric heaters, whose usage was recorded at 5-minute intervals. Preliminary metering began in November, and heating with 2 kW electric heaters began in December. It quickly became clear that additional electric heaters were needed in all of the ger except ger E, which stayed comfortable with only 2K of heat. Additional 1.5 kW heaters were added to the other ger in late December and final adjustments in the ger and sensors were completed by early January. The formal testing period began on January 25, although usage data was recorded for the 3 weeks before that time.

Annual energy consumption is estimated by calculating the amount of electric heat needed per degree temperature difference between inside and outside. This is relatively constant number, but can also be sensitive to changes in the envelope and especially to changes affecting infiltration of air. Figure 9 charts the daily figures for each of the ger through the testing period, with electric consumption, average indoor and outdoor temperatures, and the electric energy used per degree temperature difference. The calculation was averaged for each week of the electric heating periods to provide a more readily compared metric,

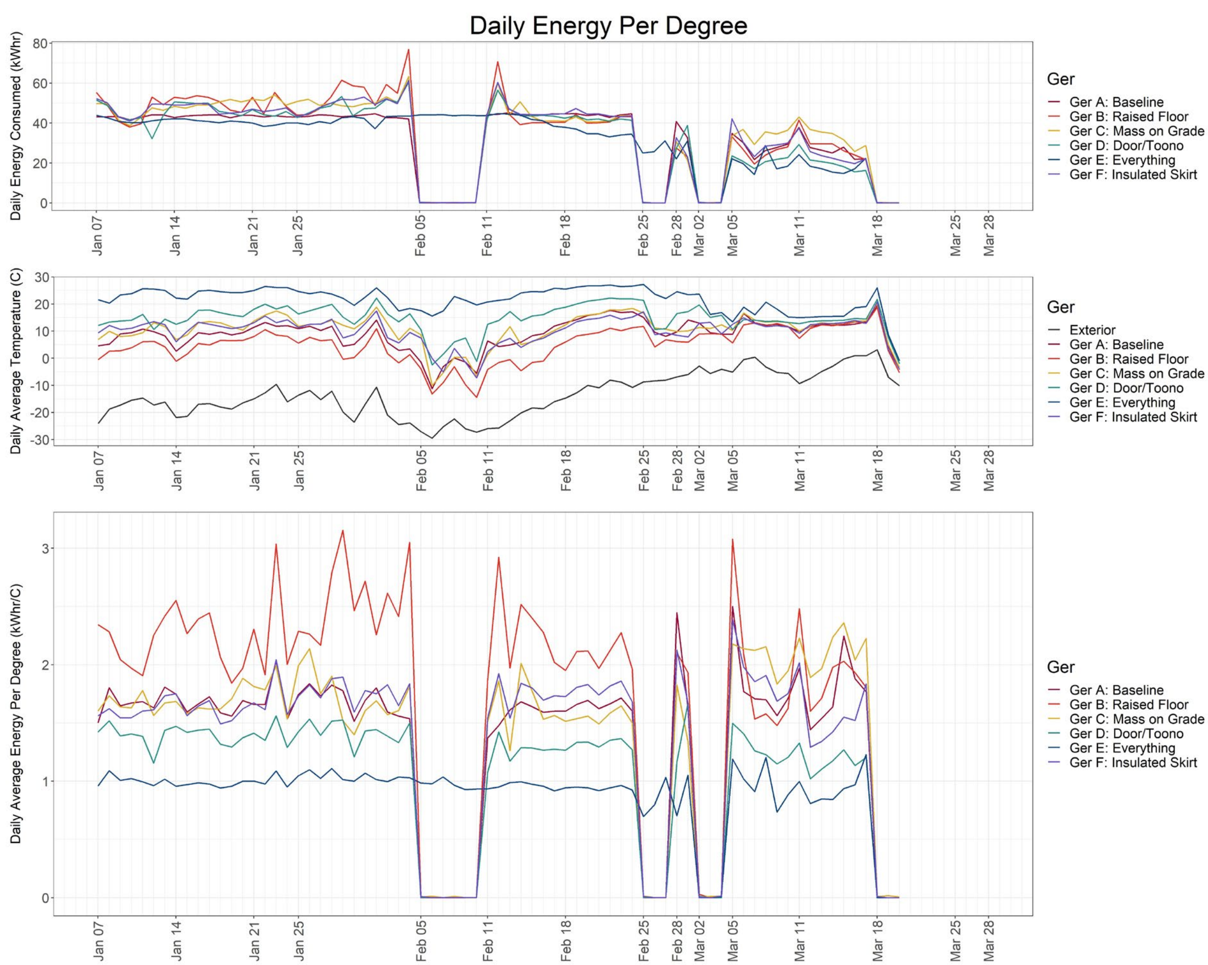

Figure 9. Daily performance of the 6 test ger over the twelve weeks of testing period. Upper chart shows actual electric consumption of each ger, middle chart shows the average temperature inside and outside, and the lower chart shows the electricity per degree

plotted in Figure 10 and presented in Table 3. The relative performance of the six ger is clearly evident in the weekly performance with the Everything Ger (E) using the least energy and the Raised Floor Ger (B) needing the most. The other two floor prototypes, Mass on Grade Ger (C) & Insulated Skirt Ger (F), were very close to the Plain Ger (A) in energy use, though the interior temperatures of Ger C were consistently higher. On average the Door/Toono would need 25% less energy that Ger A, while Ger E would use 45% less

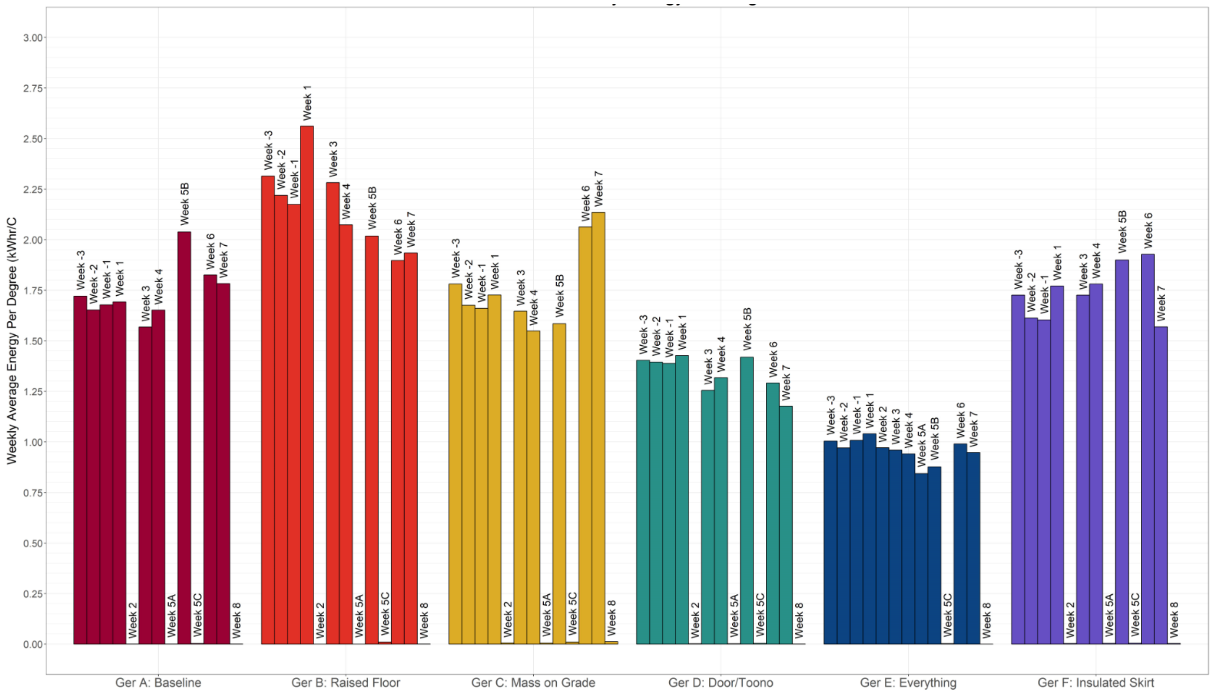

Figure 10. Weekly performance of the 6 test ger over the twelve weeks of testing period. Performance is plotted as electric heater consumption per degree temperature difference between inside and outside (kWh/C)

The average ger in the ger district spends about $250 on wood and coal though the season, and an additional $60-$120 on electricity for other devices during winter months, which also contribute heat to the interior. In this calculation, an affordable, electrically heated ger would have to use less than $320 to $370 of electricity for the six months of winter.

Ger A, the Plain Ger, was constructed and insulated like a standard 5-panel ger to provide a point of reference for the different improvements. It would cost about $600 to heat with electricity through an average winter.

Ger B, the raised floor prototype would use about $700 to heat through an average winter. The space under the insulated floor was not well sealed at the edges, so the air space was mostly at the same temperature as the outdoors, meaning that it became a greater source of heat loss than the traditional wood floor directly on ground. Ger B did have an outdoor air intake installed on the stove in the first week of March, which accounts for its improved performance in the second half of the testing period and the lower infiltration rate recorded in the test (see section on infiltration).

Ger C, a floor prototype with concrete tiles set on a layer of insulation on the ground, would require roughly as much heat as the plain ger. The use of an exposed concreate block at the edge of the floor increased the heat flow out the edge, outweighing the reduction of heat transfer into the ground. To make this floor prototype successful will require an insulating detail at the edge of the floor where the

temperature differences and heat loss are greatest.
The theory of including the concrete tiles is that the thermal mass of the tiles would store and release heat and the additional mass appeared to have an effect on the average interior temperatures, keeping them a couple of degrees higher than the plain ger. This effect would be enhanced if the floor received heat more directly, like the clay of the western style ger stoves. Ger C also exhibited decreased performance in the weeks after the coal tests, when nighttime interior temperatures dropped below freezing, so the charging and discharging of the heat in the thermal mass is an important dynamic factor in this prototype.

Ger D, the Door/Toono ger had an insulated door covering designed by Arc'teryx and an insulated toono covering designed by North Face, both of which increased insulation levels and sealed likely sources of infiltration. This prototype used considerably less energy than the Plain Ger, and would require about $450 per year to heat with electricity. Looking at the results week-by-week, it shows that the removal of the door insulation in week 3 had a minimal effect, suggesting that the toono cover alone may have kept the infiltration low (see infiltration section). The infiltration tests only occurred after the door insulation removal, so that effect can't be confirmed. Ger D had a floor detail similar to ger A, a wood floor set directly on the ground, so the floor edge was also better insulated than those of the floor prototypes.

Ger E, the everything ger had an insulated floor placed on directly on the ground, more insulation in the walls and roof, and an insulated door and toono cover. On average, the everything ger would require about $325 to heat with electricity, making it comparable to coal and wood. The floor of Ger E had a wood floor resting directly on a thick layer of insulation, so the edge was considerably better insulated than those of the floor prototypes.

Ger F, had an insulated skirt inserted vertically in the ground around the perimeter to reduce heat loss. Like Ger C, it would require about the same amount of electricity to heat through a typical winter as Ger A, and also like Ger C, it maintained a higher interior temperature. This suggests that while the insulation did reduce heat flow into the ground, making the most of the floor surface warmer, there may have been heat leakage at the edge where the wall meets the ground and the temperature differences are greater. Because of the slope of the site, about half of the insulated skirt was elevated about average ground level exposing it to outdoor air temperatures and increasing the edge losses in that section.

Table 3. Weekly degree day analysis of six ger prototypes, showing average interior temperature, annual heating energy, annual cost, and the ratio of annual heating needed to heating needed by Ger A

	Week #	-1	-2	-3	1	2	3	4	5A	5B	5C	6	7	8	Avg
						Coal			Coal		Coal			Coal	
Ger A	Avg °C	8	8	12	8.2	-3.8	7.3	15.9	10.9	11.9	10.4	12.5	12.1	6.6	
	kWh/yr	11,996	11,516	11,692	11,794	5	10,926	11,510	5	14,200	26	12,719	12,426	4	
	$/yr	592.6	568.9	577.6	582.6	0.3	539.8	568.6	0.3	701.5	1.3	628.3	613.9	0.2	**$606**
Ger B	Avg °C	3.6	4.4	8.8	3.9	-8.9	-1.3	9.3	7.6	6.1	9.0	11.3	11.7	5.4	
	kWh/yr	16,127	15,462	15,149	17,848	2	15,900	14,446	2	14,061	71	13,219	13,481	3	
	$/yr	796.7	763.8	748.4	881.7	0.1	785.5	713.6	0.1	694.6	3.5	653.0	666.0	0.1	**$732**
	Ratio B/A	1.34	1.34	1.30	1.51		1.46	1.26		0.99		1.04	1.08		**1.22**
Ger C	Avg °C	10	11	16	12	-2	7	16	13	10	12	14	13	7	
	kWh/yr	12,407	11,676	11,568	12,031	43	11,469	10,788	39	11,039	69	14,375	14,878	89	
	$/yr	612.9	576.8	571.4	594.3	2.1	566.6	532.9	1.9	545.3	3.4	710.1	735.0	4.4	**$614**
	Ratio C/A	1.03	1.01	0.99	1.02		1.05	0.94		0.78		1.13	1.20		**1.02**
Ger D	Avg °C	13	16	19	17	4	15	21	14	17	17	13	14	9	
	kWh/yr	9,782	9,718	9,673	9,945	14	8,746	9,180	15	9,888	30	9,002	8,201	3	
	$/yr	483.2	480.1	477.8	491.3	0.7	432.1	453.5	0.7	488.5	1.5	444.7	405.1	0.1	**$453**
	Ratio D/A	0.82	0.84	0.83	0.84		0.80	0.80		0.70		0.71	0.66		**0.75**
Ger E	Avg °C	24	24	26	22	19	23	26	24	24	19	17	16	11	
	kWh/yr	6,999	6,761	7,024	7,249	6,767	6,687	6,560	5,876	6,114	18	6,903	6,602	0	
	$/yr	345.8	334.0	347.0	358.1	334.3	330.4	324.1	290.3	302.0	0.9	341.0	326.2	0.0	**$326**
	Ratio E/A	0.58	0.59	0.60	0.61		0.61	0.57		0.43		0.54	0.53		**0.55**
Ger F	Avg °C	12	11	14	11	0	6	14	12	8	12	13	12	7	
	kWh/yr	12,026	11,236	11,174	12,343	23	12,026	12,408	29	13,238	36	13,435	10,933	26	
	$/yr	594.1	555.1	552.0	609.7	1.2	594.1	612.9	1.5	654.0	1.8	663.7	540.1	1.3	**$612**
	Ratio F/A	1.00	0.98	0.96	1.05		1.10	1.08		0.93		1.06	0.88		**1.02**

2. Air Infiltration.

The infiltration of outdoor air can be a significant source of heat loss in buildings, with colder outdoor air displacing warmer indoor air. The rate at which air infiltrates buildings has been researched for decades, with a great deal of progress after the energy supply crises of the 1970s. Air leakage is largely driven by two environmental factors, the temperature difference between inside and outside, the so-called “stack effect,” and wind pressure, which varies according to the wind speed and the particular shape and exposure of the building. Infiltration is commonly described by an air-change rate, the number of times the volume of air inside the building is replaced in an hour (ACH), which ranges from less than one to 10 ACH or higher for leaky structures.

There are two widely accepted techniques for evaluating the air change rate or leakiness of a building structure. In one, air infiltration under normal operating conditions is determined by introducing a tracer gas into the interior and then measuring the rate at which it is diluted by outdoor air. Carbon Dioxide (CO2) is the most common gas because it is stable, inexpensive, and relatively easy to measure. Tracer gas measurements can be very accurate, but because infiltration is sensitive to temperatures and wind speeds, it can be necessary to conduct multiple tests to fully characterize the amounts of infiltration under different conditions.

The other common technique is to pressurize the building using a large fan mounted in an adjustable door, called a “blower-door,” and to use the fan to measure the air leakage rate at the higher pressure of the test (conventionally 50 Pascals). Although the pressure is unnaturally high, it provides a simple, reproducible test now widely used in building performance standards, both during construction and as an auditing tool for older buildings. It is also commonly combined with visual inspection of the envelope using infrared thermography, because the greater pressure intensifies the leakage of colder or warmer air, making them more visible.

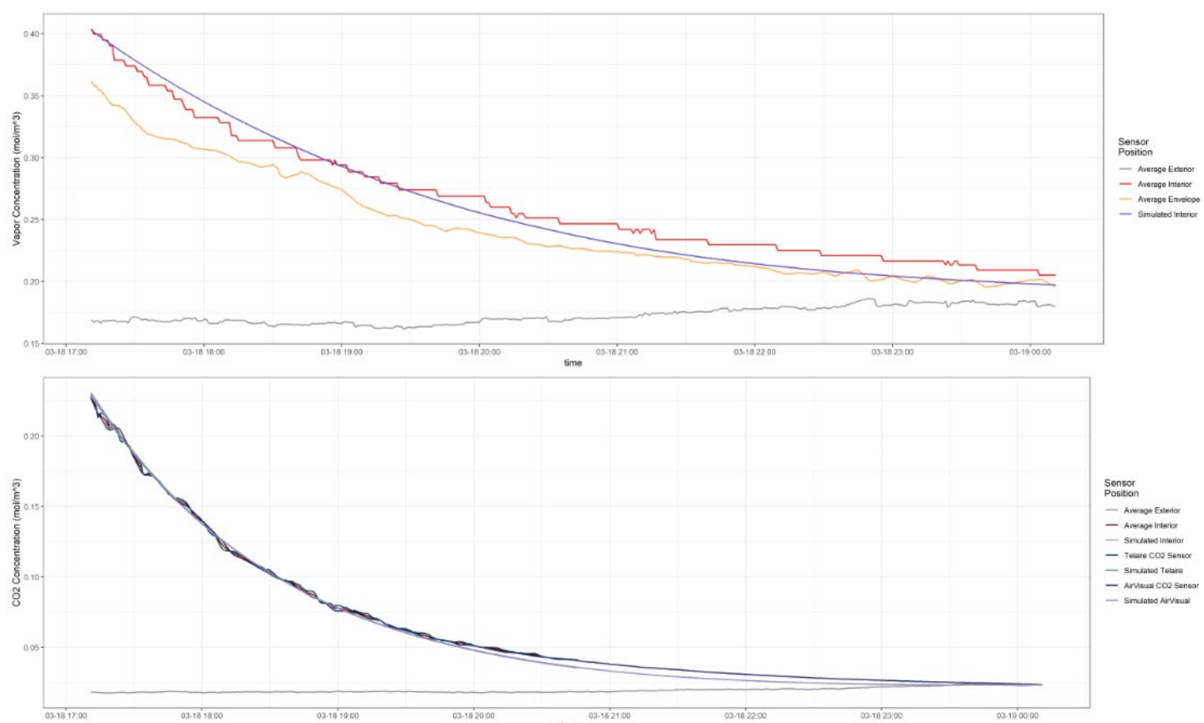

Figure 11. Infiltration test #8 at Penn Ger, showing test with moisture from humidifier (above) and CO2 (below)

The use of a blower-door on ger was ruled out because of the general porosity of ger construction, so infiltration tests with CO2 as a tracer gas were conducted at the Penn Ger. These were intended to provide a first-order comparison of infiltration rates between the ger heated with electricity and with the coal stove, so that heat loss pathways could be better characterized. We did not have the capacity to conduct CO2 tests on the ger in Mongolia, so we tried a technique using water vapor instead of CO2. In that test a standard room humidifier was used to increase the humidity level inside the ger and then we measured its rate of decline when the humidifier was turned off. Moisture interacts more dynamically with the interior environment—by absorption and condensation—complicating its use in this kind of test. Figure 11 shows the infiltration test #8 at the Penn Ger using both moisture and CO2. This was among the most successful of the moisture tests, but it identified an infiltration rate roughly half that determined with CO2, though the relative performance between tests was similar.

Penn Ger

Table 4 summarizes the results of the 11 infiltration tests conducted on the Penn ger. These were done over the period of a few weeks and sought to answer a number of different questions. In addition to the comparison between electric and coal heating, we introduced an outdoor air intake for the coal stove in two tests and also combined some of the infiltration tests with the cool-down benchmark tests. The outdoor air intake was somewhat makeshift and according to the data, it perversely increased the rate of infiltration, which was likely due to the imperfect penetration through the envelope. The rest of the tests did confirm the expectation that firing a coal stove (with a chimney) noticeably increases the rate of air infiltration. When the ger was heated with electricity and the toono was fully covered, the measured rates of infiltration were between 0.8 to 1.5 ACH. With the coal stove operating, pulling air up the chimney, the rates were between 2.2 to 3.9 ACH, roughly two to three times higher. Even higher rates were measured when the door and toono were left partly to all the way open, giving rates of 5 to 12 ACH.

Table 4. Results of infiltration tests at Penn Ger, using both CO2 and water vapor

Test	Date	Heat	Test Conditions	Vapor Test		CO2 Test (Avg)		Ambient Conditions			
				Infiltration Rate (m^3/s)	Infiltration Rate (ACH)	Infiltration Rate (m^3/s)	Infiltration Rate (ACH)	Exterior RH (%)	Interior Temp (C)	Exterior Temp (C)	Heater Power (kW)
1	2/26	None	Heater Turns off at Beginning of Test	0.0089	0.7	0.0098	**0.8**	45.06	8.35	1.47	0
2	3/5	Coal	No Outdoor Air Intake; Stove Burns Out	0.0057	0.5	0.0269	**2.2**	45.84	15.35	-2.7	0
3	3/6	Coal	Outdoor Air Intake; Stove Burns Out	0.0053	0.4	0.0482	**3.9**	44.18	18.21	-4.19	0
4	3/7	Coal	Outdoor Air Intake; Stove Stays Lit	0.0045	0.4	0.0433	**3.5**	50.7	43.64	-0.36	0
5	3/8	Coal	No Outdoor Air Intake; Stove Stays Lit	0.0021	0.2	0.0289	**2.3**	86.81	49.33	2	0
6	3/11	Electric	Thermostat	0.0009	0.1	0.0054	**0.4**	37.49	19.49	8.42	0.84
7	3/16	Electric	Thermostat	0.0029	0.2	0.0193	**1.5**	42.38	15.8	2.02	0.84
8	3/18	Electric	Thermostat	0.0043	0.3	0.0087	**0.7**	45.09	22.17	5.4	0.83
9	3/21	Electric	Thermostat - Door Open	0.0114	0.9	0.0626	**5.0**	94.62	19.69	9.39	0.84
10	3/26	Electric	Door Open; Toono Partially Uncovered	0.027	2.2	0.122	**9.8**	22.66	15.94	5.74	0.83
11	3/28	Electric	Door Open; Tonno Mostly Uncovered	0.0413	3.3	0.1508	**12.1**	55.41	18.48	10.75	0.83

Test Ger

Two rounds of infiltration tests using moisture were conducted on the Test Ger, and results are tabulated in Table 5. Except for the first test on ger F, the infiltration results have good statistical correlation, so they provide reasonable comparative measures of infiltration. Using moisture in Mongolia to evaluate infiltration is complicated by the extreme variations in temperature inside and outside of the ger, and the

Table 5. Results of infiltration tests at Test Ger, using water vapor as the tracer gas

Test	Ger	Date	Heat	Test Conditions	Vapor Test				Ambient Conditions			
					Infiltration Rate (m^3/s)	Infiltration Rate (ACH)	RMSE	R^2	Exterior RH (%)	Interior Temp (C)	Exterior Temp (C)	Heater Power (kW)
1	A	3/3/2019	Coal	2 firings, cool down at night	0.0216	**1.7**	0.0085	0.7400	41.19	15.67	-5.83	0
1	B	3/3/2019	Coal	2 firings, cool down at night	0.0111	**0.9**	0.0030	0.9717	40.89	14	-5.76	0
1	C	3/2/2019	Coal	2 firings, cool down at night	0.0364	**2.9**	0.0073	0.7521	51.15	9.15	-7.91	0
1	D	3/2/2019	Coal	2 firings, cool down at night	0.0402	**3.2**	0.0097	0.7435	50.57	9.62	-7.73	0
1	E	3/4/2019	Coal	2 firings, cool down at night	0.0229	**1.8**	0.0092	0.9073	49.17	20.33	-3.86	0
1	F	3/4/2019	Coal	2 firings, cool down at night	0.1007	**8.1**	0.0262	-4.9591	49.17	12.38	-3.86	0
2	A	3/6/2019	Electric	Thermostat	0.0149	**1.2**	0.0025	0.9480	25.15	15.31	-0.12	1.22
2	B	3/6/2019	Electric	Thermostat	0.0060	**0.5**	0.0043	0.7798	25.15	15.98	-0.11	1.15
2	C	3/5/2019	Electric	Thermostat	0.0182	**1.5**	0.0052	0.9272	40.65	19.22	-6.15	1.89
2	D	3/5/2019	Electric	Thermostat	0.0202	**1.6**	0.0037	0.9741	40.65	17.07	-6.15	1.03
2	E	3/7/2019	Electric	Thermostat	0.0111	**0.9**	0.0050	0.9637	30.28	17.5	-0.81	0.76
2	F	3/7/2019	Electric	Thermostat	0.0231	**1.8**	0.0039	0.9491	29.96	15.24	-0.72	1.17

dynamics of the daily moisture cycle are discussed in section 4.

In general, the tests showed the expected higher infiltration rates when the coal stoves were being fired and drawing more air through the chimney. They are roughly twice as high with the stove as when heated with electricity. Ger B did have an outdoor air intake installed on its stove before the infiltration testing, so this likely accounts for it having the lowest infiltration rate. Unfortunately, with only the two cycles of tests, the comparative value of the tests is limited.

Figure 12 shows the complications that occur in even a fairly successful infiltration test using moisture. Toward the end of the test the interior vapor concentration actually drops below the exterior vapor concentration, meaning that moisture is being removed from the air by other mechanisms besides air infiltration. The most likely mechanism is condensation on the cold surfaces within the roof and walls, and even on surfaces within the interior as the ger is allowed to cool below freezing over night.

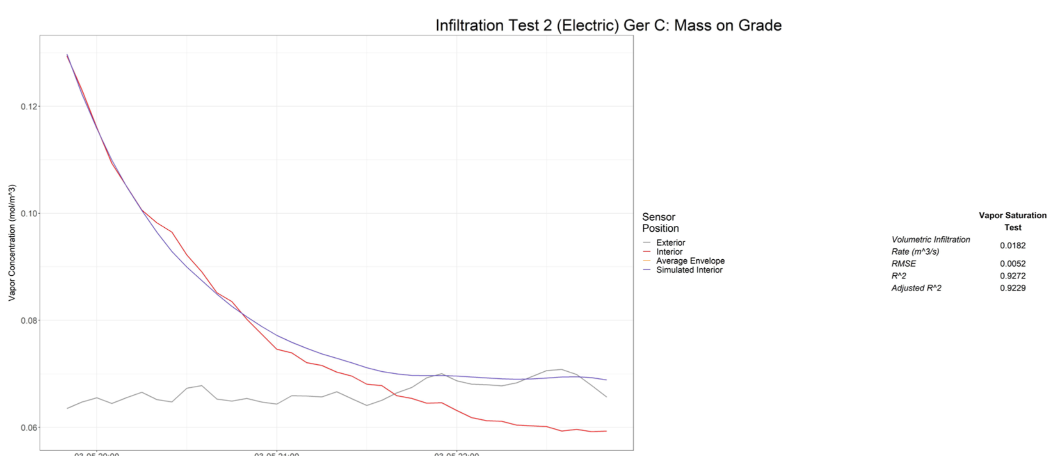

Figure 12. Results of infiltration tests at Test 2 in Ger C, using water vapor as the tracer gas

Occupied Ger

It was not possible conduct infiltration tests on the occupied ger, however indirect evidence from the installation of the door insulation prototype in ger 4 shows the effect of reducing air flow. The door insulation was moved from Ger D at the test ranch to ger 4 on February 16. Figure 13 shows the air and stove temperatures before and after that change. The number of coal stove firings was reduced from 3 per day to 2 per day, and the highs and lows were moderated, making the interior more comfortable.

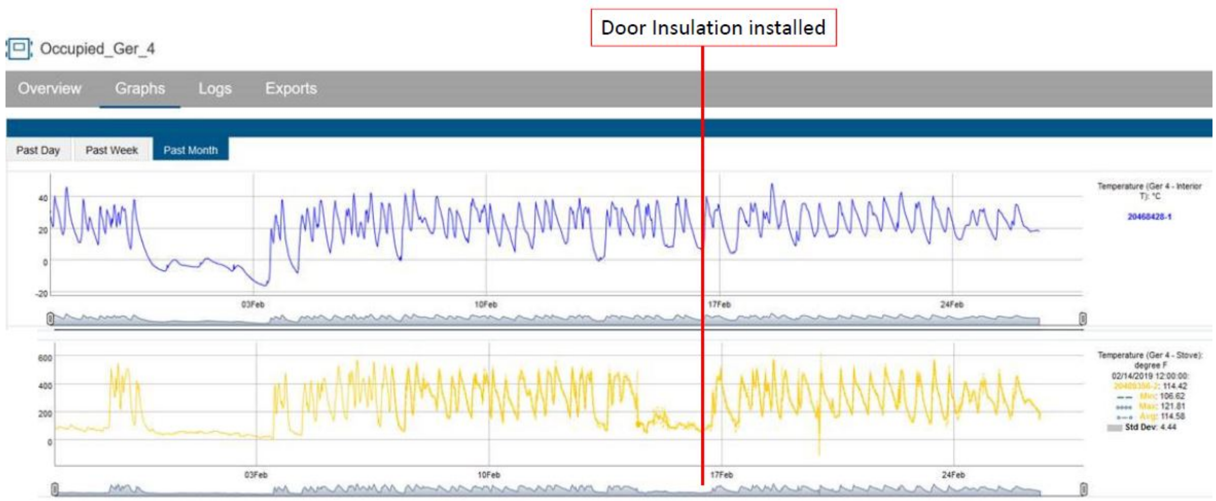

Figure 13. Air and stove temperatures in Occupied Ger 4 before and after installation of door insulation, showing decreases in coal firing cycles from 3 per day to 2 per day

3. Thermal load analysis

In the first year of the research, a number of lumped-parameter, gray-box models were tested to find the simplest model that would fit the ger data (see Appendix). Generally, the interior temperatures of a ger are determined by a combination of inherent thermal characteristics, like insulation levels or leakiness, and dynamic disturbances, largely weather. Once an appropriate model is identified, it can be used to evaluate those thermal characteristics. This makes it possible to both compare the performance of different ger and to evaluate the different pathways by which heat is lost from a particular ger.

Steady State Analysis

Simplified, steady-state techniques are commonly used to estimate the heat loss from buildings in order to size heating equipment. They are based on a single interior temperature with no dynamic storage effects. They use typical assemblies and standardized building materials, so are not well developed for ger construction, however they provide a useful starting point for analysis and describe the expected magnitude of different pathways of heat loss.

For Ger A, two versions were modelled, one for electric heat and one for coal heating with its higher rate of infiltration. The models use estimates for the insulating value of felt, air infiltration rate, and the effective insulation at the edge of the floor. For the electric heated version it predicts an annual heat load of 11.472 kwh/yr and for the coal heated version it predicts 13,980 kwh/yr. These are close to the values measured, though they do not account for the heat released by people and electric equipment inside. The electric version shows that half of the heat loss is through the envelop, with about a quarter lost through infiltration and another quarter through the slab edge. The higher infiltration rate in coal version becomes almost as the dominant factor. Figure 14

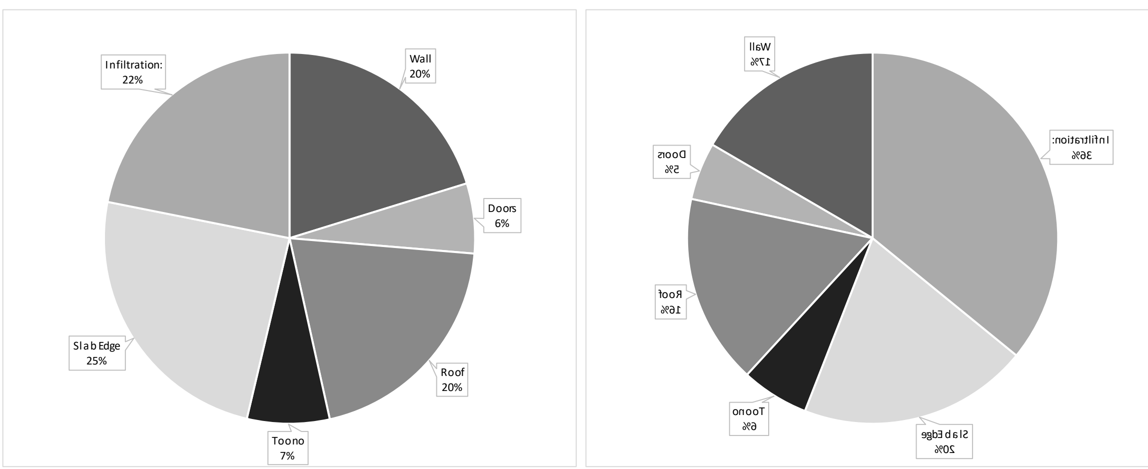

Figure 14. Heat loss pathways predicted by a steady state model for electric heat (left) and coal heat (right)

This simple comparison highlights the sensitivity of the ger to air infiltration, and the importance of improving all the pathways of heat loss together.

Dynamic Analysis

The analytical models described in Appendix D, with multiple interior temperatures, dynamic storage effects, and the effect of ground temperatures, are used to evaluate the magnitude of different heat loss pathways in the Test Ger.

Figure 15 shows the result of model 3a applied to predict the temperature of Ger E in week 1 (yellow

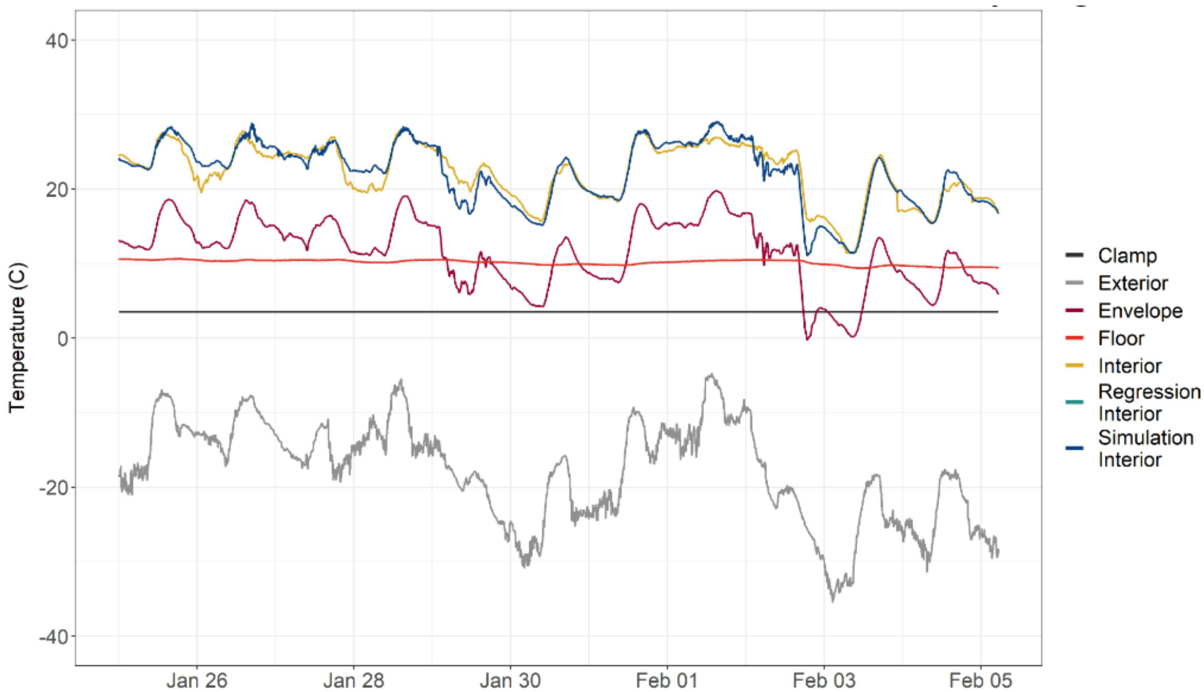

Figure 15. Model 3a use to predict temperatures for Ger E in week 1, showing close tracking of measured temperature

line). It was solved with a regression technique (green line) and an initial value solution (blue line). The two solutions were in close agreement and had R^2 values of 0.86.

Using that same model, Figure 16 shows a summary of the average hourly heat gains and losses in the six Test Ger for week 1, which distinguishes between heat going through the envelope (walls, roof, door, and toono), through infiltration , into the ground through the floor, and out the edge of the floor. This analysis provides the clearest picture so far of the relative importance of the losses through the floor edge, which range from 15-25% of the total heat loss from the ger. None of the floor prototypes really enhanced the insulation of the floor edge at the joint with the wall, relaying on the traditional canvas covering and piled dirt, which reduces infiltration at the joint but doesn't add much insulating value. The edge will be an important detail to address in developing a 21st century ger. The most promising approach would be to develop some interlocking or lapping detail between skirt insulation and the wall insulation.

The losses directly to the ground are much smaller, but contribute to raising the temperature of the floor, which affects comfort. As the comparative analysis using electric heating suggested, the insulated floor prototypes B, C, and F did not reduce the energy used to heat the ger, though they did raise the average interior temperature. The warmth of the floor is an important factor in the comfort of an all-electric ger that doesn't have the concentrated warmth of a stove to balance the temperature of the floor.

The dynamic model also includes a factor for the sunlight absorbed by the roof and walls, which offsets some of the heat loss in the ger. This factor could be enhanced by using a darker colored exterior cover, which could potentially double the amount of sun absorbed.

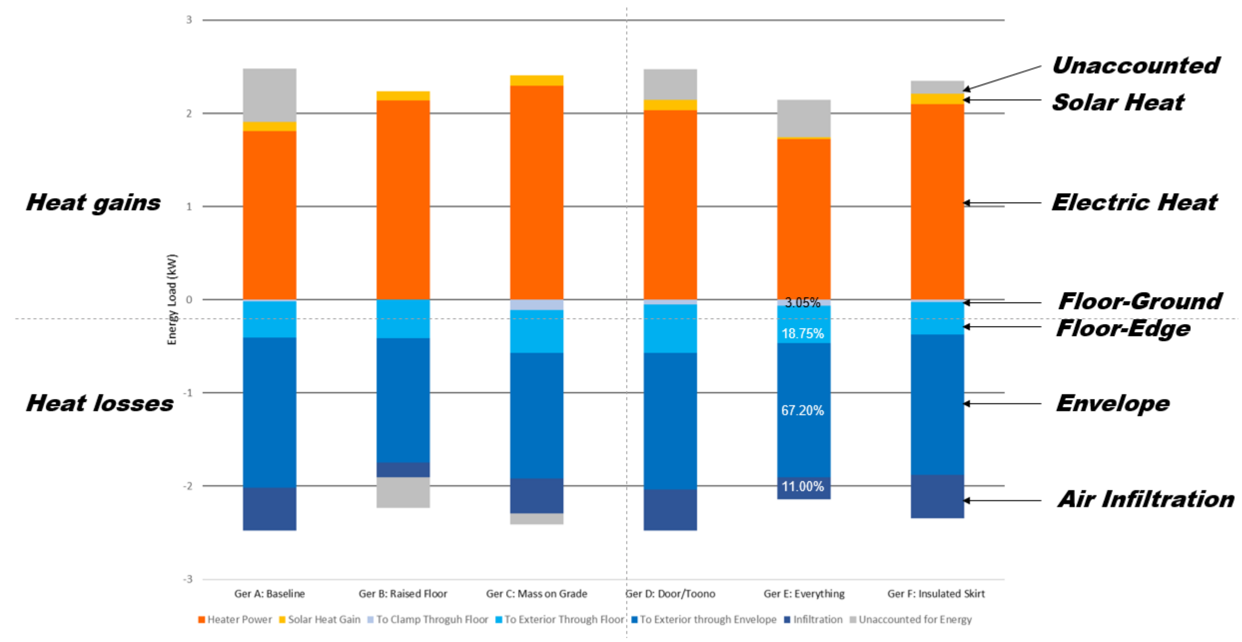

Figure 16. Average heat loss in week 1 through different pathways using model 3a

4. Moisture Dynamics

The movement of water vapor through buildings, and especially its condensation as liquid water, is a big contributor to the decay of building materials. Managing water is a critical aspect in the construction of standard buildings and will be an important consideration in the development of permanently located ger.

Even though Mongolia is a very dry climate, especially in winter, there can be significant condensation of water vapor because of the extreme temperature differences. In an occupied ger the moisture inside comes from people and their activities, from cooking, washing, and breathing. Much of that moisture is carried away by the air that leaks through cracks and openings, but some of it is absorbed in building materials, especially fabrics and felt, and some of it condenses as liquid water when it encounters surfaces colder than its “dew point” temperature (literally the temperature at which dew forms). The major location of moisture condensation is usually the inside surface of the first cold moisture barrier that the air encounters, which in ger construction will be the inside surface of the outer canvas or nylon layer.

Even in an unoccupied ger, the interior traps some moisture in a daily cycle, which is illustrated in the plots in Figure 17 of typical daily temperatures and vapor concentration for ger A & E. The peak is in the afternoon when the ger is warmest, but begins to decline as soon as the sun sets and the outer surface of the ger cools to below the dew point. As moisture condenses inside the wall and roof materials, the vapor concentration in the air drops, reaching its lowest point in the early morning, and then starts to rise as the sun hits the ger and the cycle starts again. Humidity sensors (but not wetness sensors) were placed inside the felt of the wall and roof, and they show that the vapor in the felt very closely follows that of the air, confirming that the moisture passes through the fabric and felt until it reaches a colder surface for condensation. In the test ger, the amount of moisture condensing and evaporating in this cycle is between 0.5 And 0.75 liters, and will considerably higher in occupied ger.

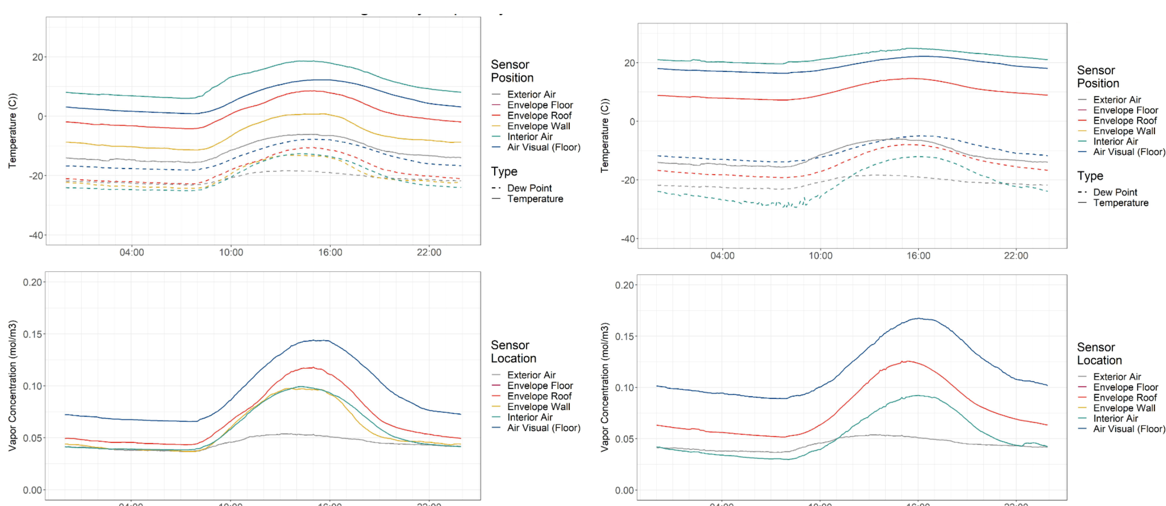

Figure 17. Average daily moisture cycle in ger A (left) and ger E (right)

The extreme temperature difference of the outer surface between night and day can even cause the interior air to become drier than that outside. The chart in Figure 18 shows the vapor concentration in ger E & F during the infiltration test conducted with a humidifier (the greater infiltration in ger F accounts for the lower peak of vapor concentration). The humidifier fills the ger with moisture, which then begins to decline when the humidifier stops and drier outdoor enters the interior. Condensation increases the drying of the interior air, especially as the ger cools overnight, and it eventually dries the air well below the outdoor levels.

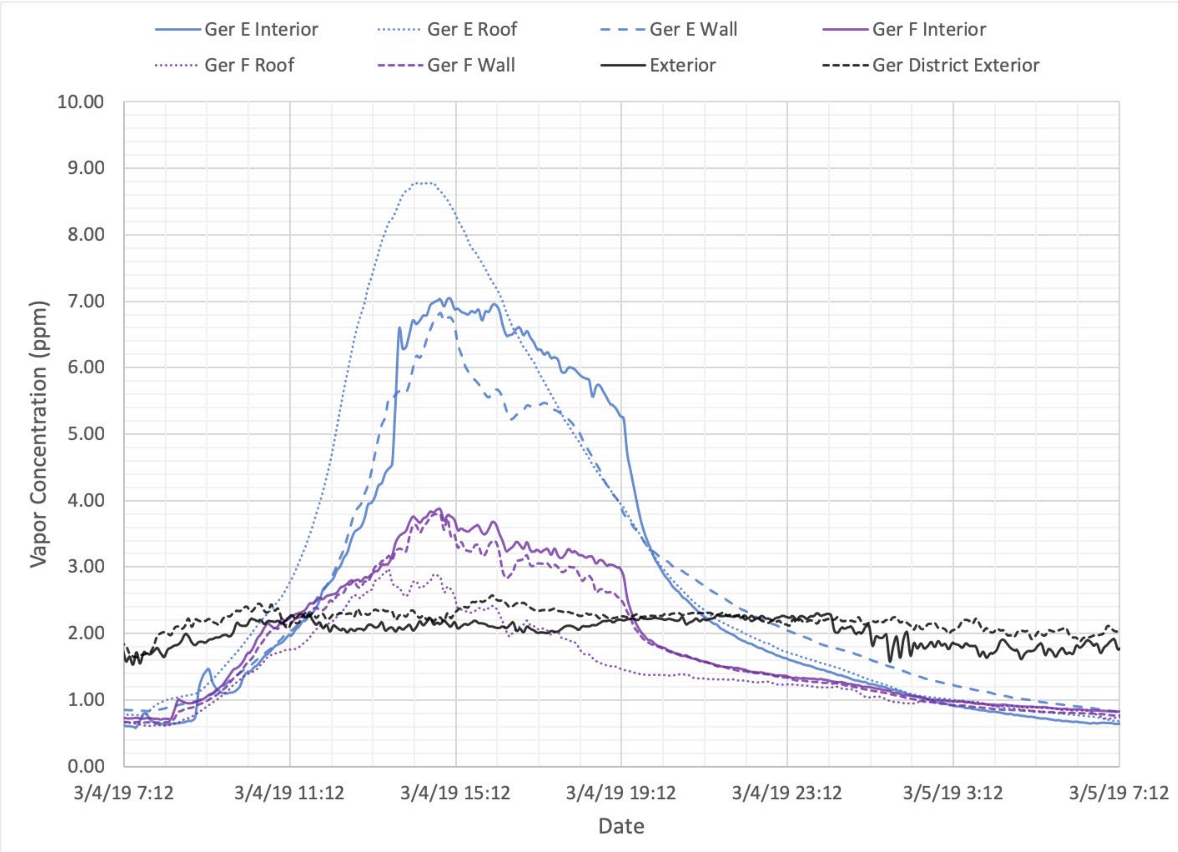

Figure 18. Moisture cycle with humidifier in ger E & F

Over time the condensation of moisture within the walls and roof of ger will hasten the decay of materials and can support the growth of molds and fungus. For highly insulated and permanently sited ger the exterior envelope should be designed to allow moisture to dissipate. Conventional construction accomplishes this with "breathing" layers or intermittent vents and similar strategies should be tested on ger.

5. Ground Heat

The thermal distribution of heat in the ground under the ger was a focus of four of the improved prototypes at the ger ranch and will be an important factor in any all-electric heating schemes. The ground in the open, under the weather station cools steadily through the winter as illustrated in Figure 19, dropping below freezing even at a meter below the ground surface. Although heat moves through soil more slowly than through air, this can represent a considerable source of heat loss in a ger with an uninsulated floor.

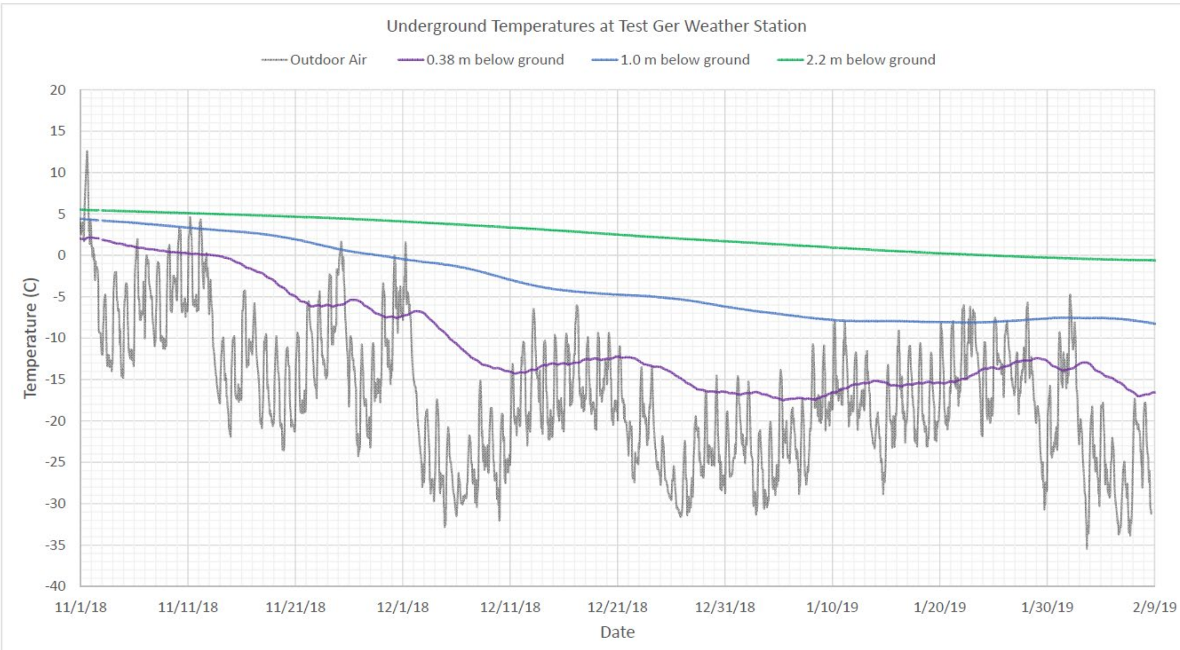

Figure 19. Air and ground temperatures at the test ger weather station

Conversely, if the soil is covered by a ger and insulated from the colder soil on either side, it will be warmed by the ger, which can stabilize the interior temperatures, making the ger more comfortable. The chart in Figure 21 shows the ground temperatures at 0.38 meter under the Test Ger through January and February with the ground temperature at the same depth under the weather station, showing temperatures between 0 and 10 °C. In general the ground temperatures at this depth directly track the interior temperatures of the ger, so ger D & E are the warmest, while ger B is only slightly warmer than the ground under the weather station.

The chart in Figure 20 shows the three temperature readings under Ger E, along with the temperatures below the weather station. The temperature at 0.38 meter below the center is the warmest, while the temperatures 1 meter below the center and 0.38 meter below the edge are 2 to 3 °C colder. This is consistent with the classic picture of a "heat ball" developing under the ger, warmest at the center and colder in a radial pattern from the center with the coldest temperatures at the edge where the heat loss is greatest. Even in Ger E, which was kept more comfortable with less energy, this reinforces the importance of better insulating the edge to reduce heat loss and increase the comfort of the interior.

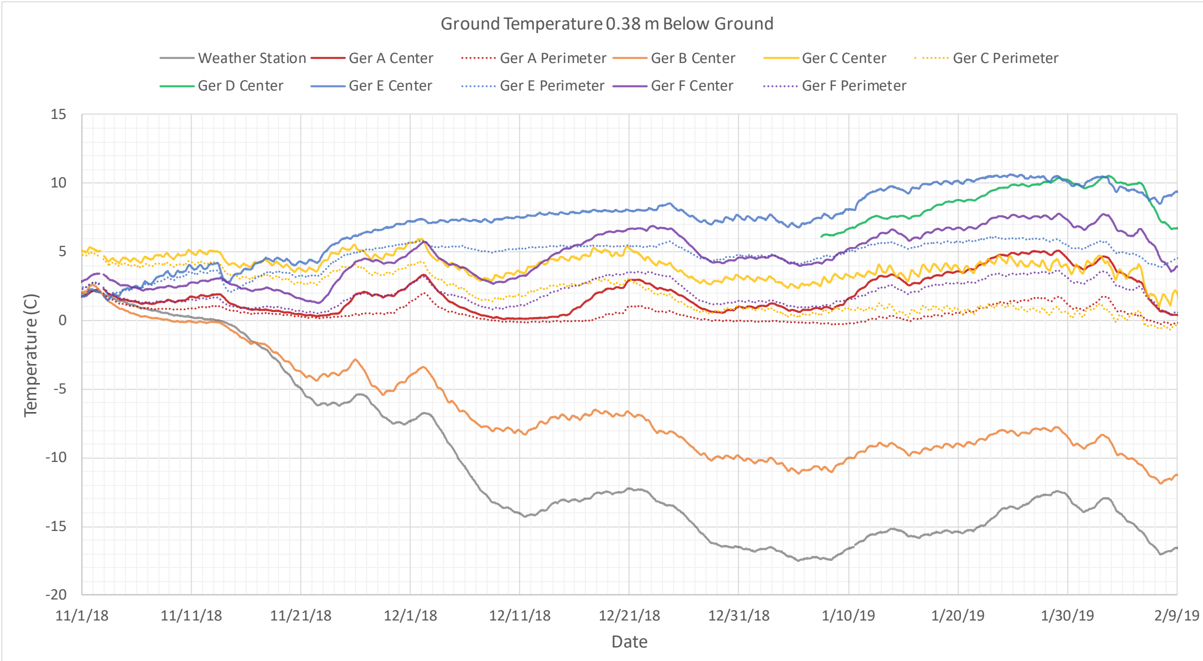

Figure 21. Ground temperatures at 0.38 meters below test ger and weather station

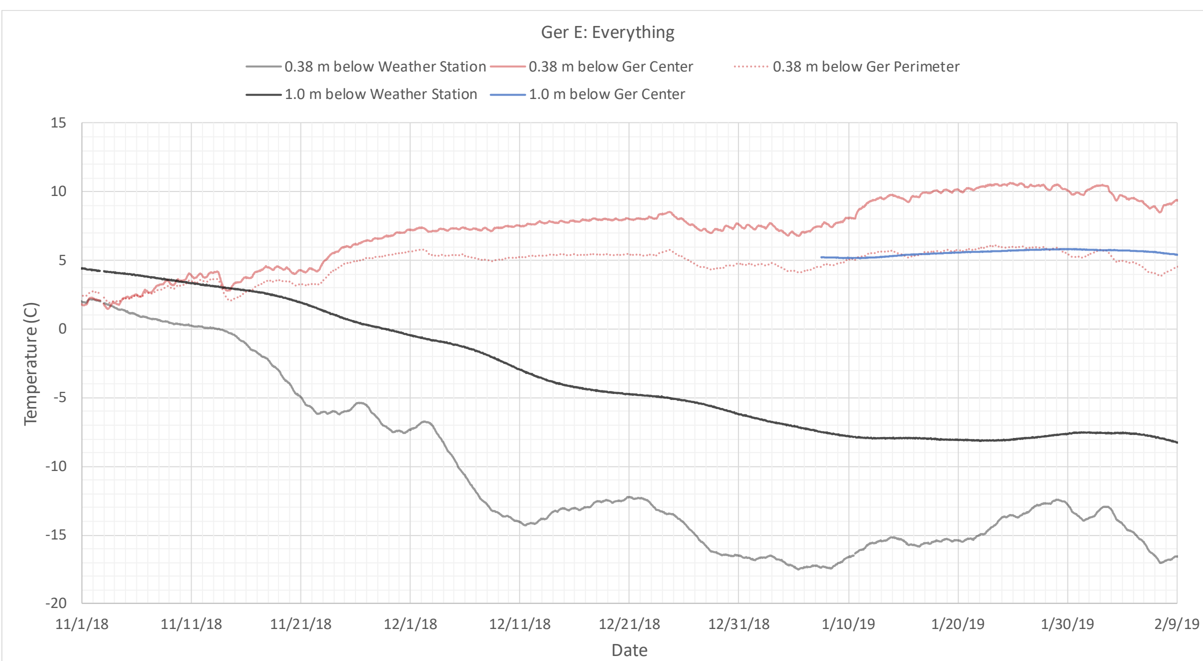

Figure 20. Ground temperatures below ger E and the weather station

21st Century Ger

The ultimate goal of the project is to design a "21st Century Ger" that can be operated without a central stove, heated affordably with electricity or other thermal sources. The principal result of the study was to demonstrate that a better insulated ger can be heated affordably with electricity.

The research set out to evaluate the different pathways of heat loss in ger and to identify techniques for reducing those losses. There are five pathways by which ger lose heat: (1) the wall/roof, (2) the door, (3) the toono, (4) the floor, and (5) by air infiltration through leaks and cracks. To reduce energy use each of the pathways must be reduced proportionally. Dramatically improving one aspect—adding many additional layers of felt for example—loses its value after the first additional layer, because heat is still flowing through the other pathways (in a leaky roof, you have to patch all the holes). The specific results for each pathway of heat loss are as follows.

1. **Wall/Roof.** Adding additional layers of insulation to the wall and roof makes a significant difference because the areas are so large. Each additional layer can reduce heat loss by 10-20% (in balance with other improvements). It can also help to add an additional vapor/wind barrier to resist the penetration of wind, though care must be taken to manage the condensation of water vapor. Ger E had three layers of felt in the walls and roof. An additional benefit can be obtained by using a darker colored exterior cover to absorb more sunlight, offsetting some of the heat losses.
2. **Door.** Adding a layer of insulation to the door makes a meaningful reduction in heat loss, and weather stripping the gaps reduces air infiltration. The research could not separate the effect of the door insulation its impact on infiltration or its interaction with the toono cover (see below), but in the Occupied ger it reduced stove firings from three times a day to two.
3. **Toono.** Adding a more insulated toono cover reduced heat loss by up to 25%, both by insulating the toono itself and reducing air infiltration. The design of an insulated toono cover will be greatly simplified if it does not have to accommodate a flue pipe.
4. **Floor.** Adding insulation to the floor reduces heat loss to the ground and increases the surface temperature of the floor, making the ger more comfortable. This will be more important in an all-electric ger without the concentrated heat of the stove. It is especially important to develop a better insulation detail for the joint between the wall and floor.
5. **Air Infiltration.** Eliminating the coal stove and chimney cut air infiltration by half and can reduce overall heat loss by 10-25%. The study was not able to examine the effect of a vestibule, but research on similar forms of construction suggest that a well-sealed vestibule can reduce the infiltration associated with regular opening of the door.

In general, Ger E, the "everything ger," provides a model for a low-cost, 21st Century Ger. However there are many regional and individual differences in ger construction, so improvements don't have to follow the exact formula used in ger E, as long as the insulating properties are improved in each of the five pathways.

Team and Sponsors

The project was funded by UNICEF with resources and in-kind contributions from the Center for Environmental Design + Planning.

The research team included a diverse mix of experts.

At the University of Pennsylvania Professor William W. Braham served as principal investigator with Evan Oskierko-Jeznacki, PhD student, leading the monitoring and data collection. Research Associate Max Hakkarainen worked on the data analysis and modelling. Michael Henry served as an expert consultant on monitoring protocols and analysis.

At KieranTimberlake Architecture, Billie Faircloth was partner in charge, with Stephanie Carlisle serving as principal and a team including Chris MacNeal, Ryan Welch, and many others.

At Arc'teryx Nathalie Marchand developed the prototype for the door insulation.

At North Face Luke Matthews developed the prototype for the toono insulation.

The project was initiated by Badruun Gardi, CEO of GerHub, a non-profit active in the ger district. The team at GerHub included Enkhjin Batjargat, Uurtsaikh Sangi, and Munkh-Orgil Lkhagva.

At UNICEF Mongolia, the project was overseen by Alex Heikens and managed by Jeremiah Mushosho and Speciose Hakizimana. Tanya Accone and Jennie Bernstein from UNICEF's Office of Innovation providing organizational support.

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Appendix A: Monitoring of Occupied Ger, Ger District

The specific monitoring equipment and their locations are as follows.

- An Onset RX3000 Data logger collected data from each of the Onset sensors and uploads it through a WiFi hotspot to the Onset web site from which it is automatically downloaded to a server at the University of Pennsylvania
- Onset Interior ambient temperature/relative humidity sensor was mounted to one of the roof sticks, approximately 5 inches from the roof, opposite the door.
- A "globe" thermometer, an Onset temperature sensor inside a black metal globe used to measure the radiant temperature of the interior, located either near the perimeter of the ger or toward the center of the ger close to the roof.
- An Onset temperature/relative humidity sensor embedded in either the roof or wall approximately opposite the door to evaluate heat flows and to detect the condensation of moisture within the insulation
- Four Omega thermocouple sensors were used to measure the following surface temperatures.
    - Stove surface temperature on the side of the stove roughly half way from the bottom of the stove in the center.
    - The temperature of the slab of material below the stove
    - The temperature of the flue approximately 30 cm below seam between two pieces of flue
    - The temperature of the floor in a slightly different location in in each ger
- A WiFi hotspot located near the datalogger
- An Air Visual air quality sensor located near the datalogger

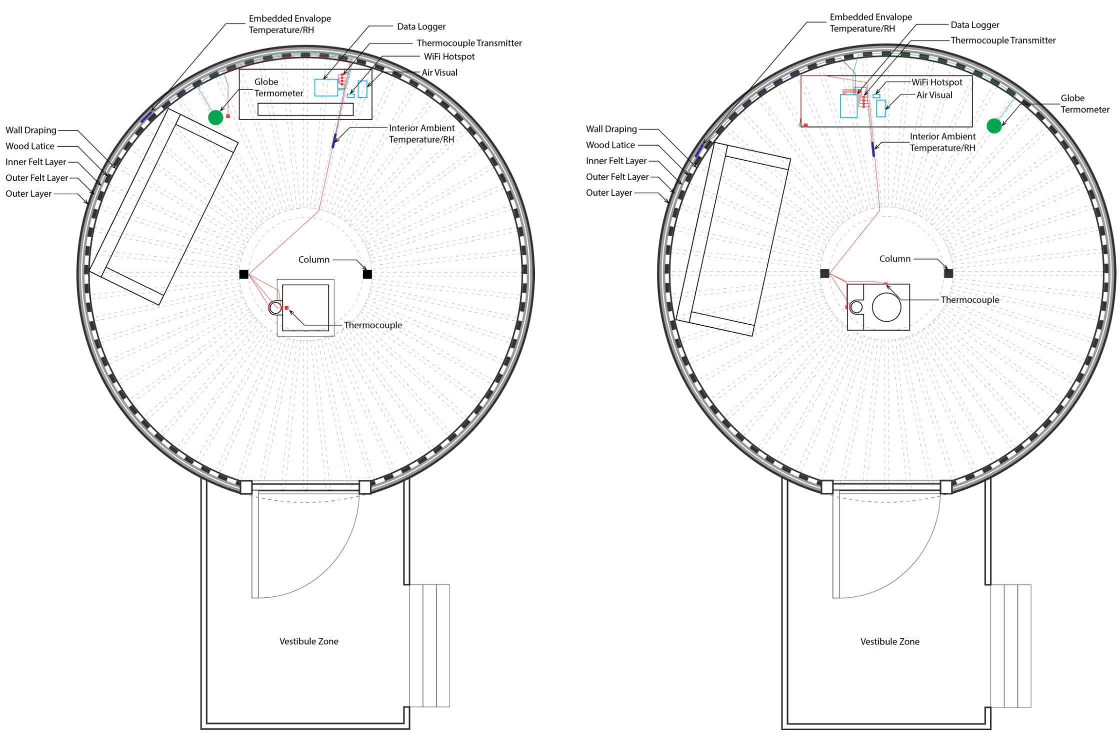


Figure X. Location of monitoring equipment in occupied ger one and two

An Onset weather station was located near the five occupied ger to capture local ambient conditions. It

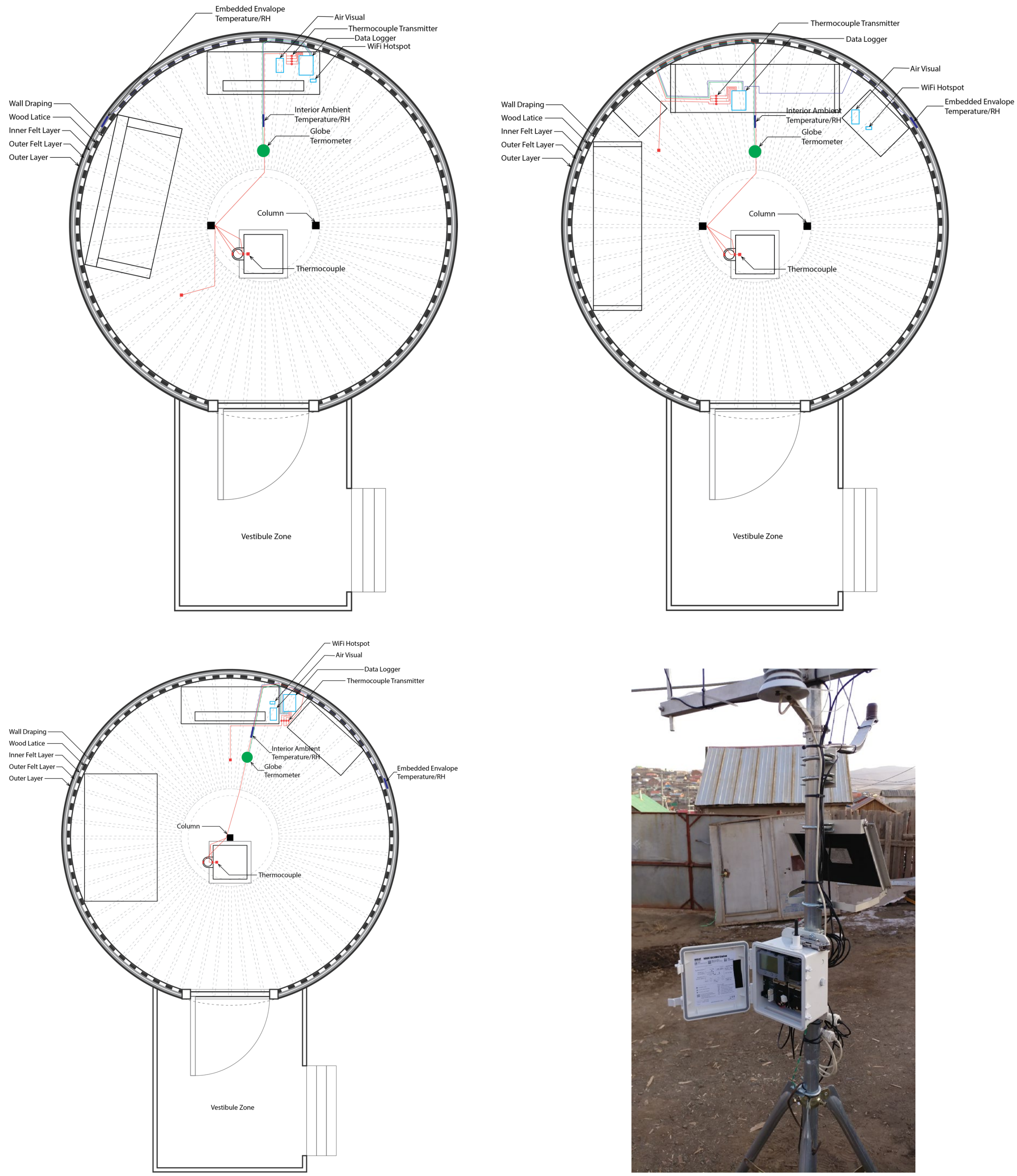


Figure X. Location of monitoring equipment in occupied ger three, four, five, and weather station

included:

- Exterior ambient temperature and relative humidity
- Wind speed
- Wind direction
- Solar Insolation

Appendix B: Monitoring of Test Ger, "Ger Ranch"

The specific monitoring equipment and their locations are as follows.

There is an electrical box in ger A with individual breakers for the heaters in each of the six test ger and another breaker for all other loads in the ger. The power is then routed from the electrical box to the rest of the ger. The weather station has wireless sensors, which are powered by batteries attached to the mast. It has the following sensors:

- Wind speed and direction
- Solar flux
- Ambient temperature and relative humidity
- Embedded ground temperature, depth 1 (0.38 m)
- Embedded ground temperature, depth 2 (1 m)
- Embedded ground temperature, depth 3 (2.2 m)

Each of the six ger have, at a minimum, the following sensors:

- Onset Interior ambient temperature/relative humidity sensor was mounted to one of the roof sticks, approximately 5 inches from the roof, opposite the door.
- Embedded Onset roof temperature/relative humidity sensor located next to the interior ambient temperature/relative humidity sensor
- Embedded Onset wall temperature/relative humidity sensor located opposite the door, approximately 1 m from the floor
- A "globe" thermometer, an Onset temperature sensor inside a black metal globe used to measure the radiant temperature of the interior, located either near the perimeter of the ger or toward the center of the ger close to the roof.
- Embedded Onset ground temperature sensor, depth 1 at 0.38 m, located near the center of the ger
- Two Omega thermocouple sensors were used to measure the following surface temperatures
  - Floor surface temperature located near the depth 1 embedded ground sensor
  - Flue/heater surface temperature located either on the flue about a foot below the seam or on the center of the front side of the electric heater
- An Air Visual air quality sensor located near near the perimeter of the ger on the floor
- Current transducers to measure the electrical consumption of the heaters (located in the circuit breaker box)

Some of the test ger have the following sensors, in addition to the basic set:

- Embedded ground temperature, depth 2 at 1 m, located near the center of the ger
- Embedded ground temperature, depth 1 at 0.38 m, located about 2/3 of the way to the perimeter of the ger
- A second globe thermometer either located in the center of the ger near the tonno or near the door, 0.9 m from the top of the wall measured along a roof stick, 1 m off the ground measured to the midpoint of the globe thermometer
- An embedded floor temperature/relative humidity (located near the depth 1 embedded ground sensor and the floor surface temperature thermocouple)
- Additional Omega thermocouples:
  - Surface temperature on the thermal mass below the stove
  - Stove surface temperature located in the middle of the face of the stove opposite the door

Some ger have additional equipment:

- Onset RX3000 Data loggers located near the perimeter of the ger
- Onset EG4115 Current Logger located in the circuit breaker box
- WiFi hotspot located near the data logger)
- HOBOnet wireless receiver
- Thermocouple transmitters
- Analog to digital sensor adaptor

The particular layouts of each of the occupied ger are shown in diagrams below.

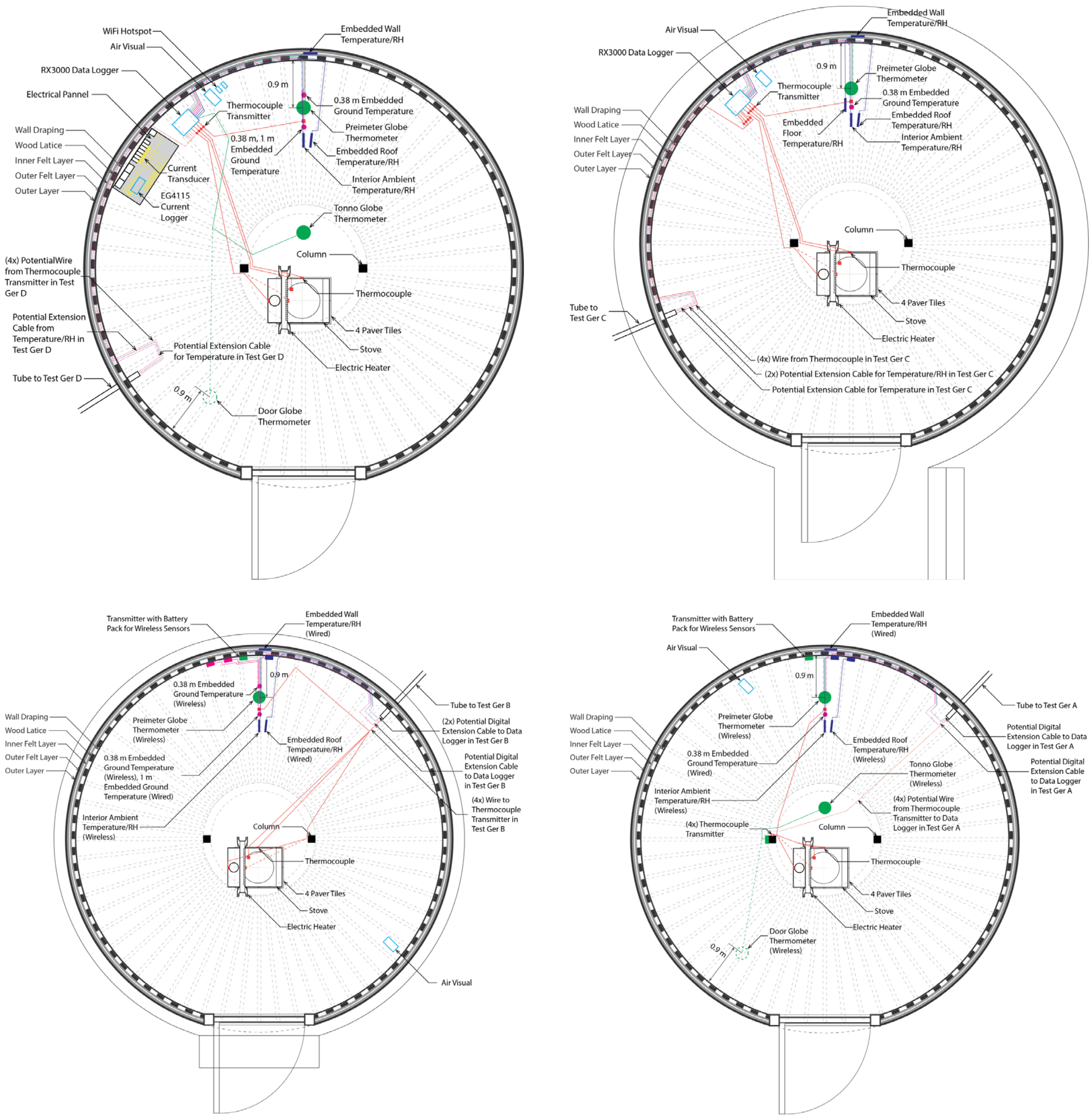


Figure 6. Layouts for monitoring equipment in ger A, B, C, & D

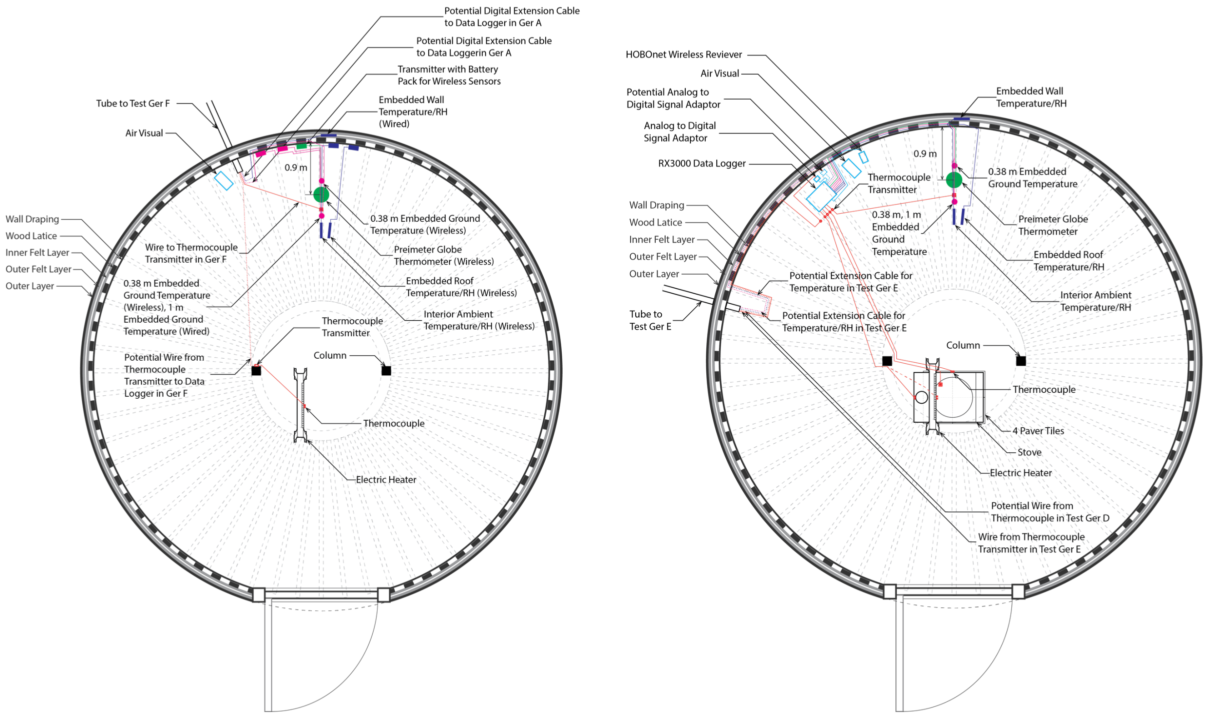
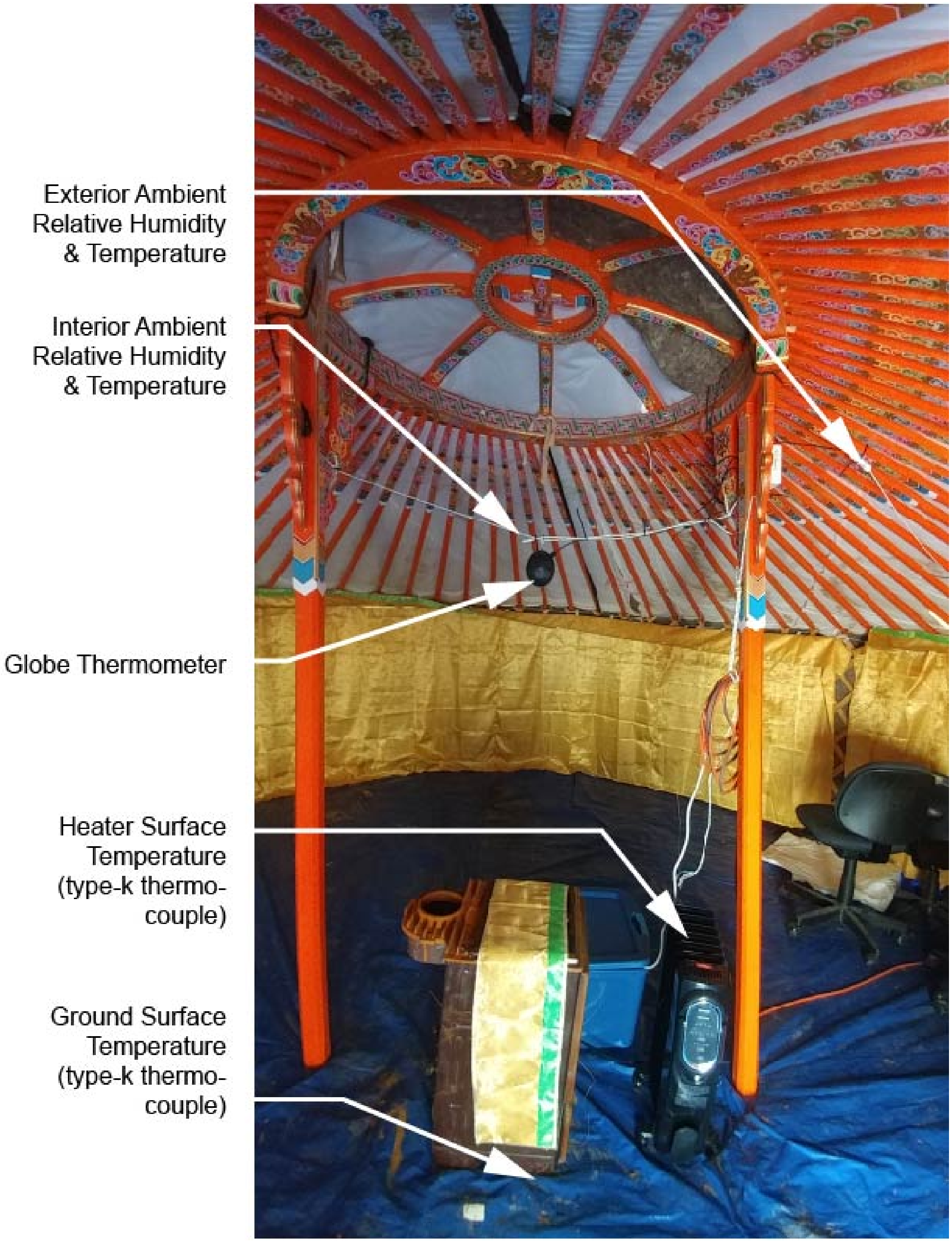


Figure 6. Layouts for monitoring equipment in ger E & F

Appendix C: Monitoring of Penn Ger, Philadelphia, PA

The specific monitoring equipment and their locations are as follows.



Appendix D: Analytical Thermal Models

A number of lumped-parameter, gray-box approaches were tested to find the simplest models to fit the data (Bacher 2011). Three different solutions were used to find dependable methods for determining the thermal parameters of the ger, the first using multiple linear regression, the second using an initial value method, and the third using a maximum likelihood method called Continuous Time Stochastic Modelling, CTSM, developed by a Danish Research group (Madsen 1995, Kristensen 2003). The regression and initial value solutions can be used to determine a thermal time constant, or cool-down time, but could not always be solved for individual thermal parameters. The advantage of the CTSM method is its ability to identify individual thermal parameters, helping evaluate the contributions or effects of the different elements.

Gray box modeling refers to a hybrid approach that integrates concepts of white and black box modeling (Khan 2012). White-box models conceptualize and model a system with detailed and accurate knowledge of its internal logic. With regard to building models, this approach requires specific information such as construction materials, occupancy schedules, mechanical systems for heating and cooling, and environmental exposure conditions. Aside from being resource intensive, white box models are also considered deterministic, as they do not account for the behavior of variables not included in the model. Conversely, black box modeling assumes no predetermined knowledge of the internal logic of a system. In other words, behavior of a system estimated using this method derives its insights strictly from analyzing the relationships between its inputs and outputs.

The value of a well-fit gray-box model is its specificity to the building as it is. The architectural complexity of the ger, or lack thereof, lends itself to modeling its thermal behavior as a "lumped system." In heat transfer dynamics, this approach assumes an ideal, uniform thermal distribution of the system (Holman 1976). As a lumped system, the thermal capacity and behavior of the air inside the ger is considered as a single volume that gains and loses heat uniformly. The symmetrical configuration and relatively small volume of the ger interior negates many of the limitations typically imposed by the lumped method.

Little is known about the precise thermal characteristics of the ger (e.g., stove, thermal mass, volume, etc.) nor the precise material properties of the ger envelope. Furthermore, these properties can vary significantly from ger to ger. What is known, to a degree, is the internal logic of the ger system, or the pathways for heat gain, storage, and loss. Even generalized, this internal logic provides a framework for quantifying these properties from recorded data. Instead of telling the computer how the building is built and asking it for the indoor temperature, one tells the computer the measured indoor temperature and asks it for the building parameters – parameters describing what the building is like.

Models of increasing complexity are used to evaluate the pathways of heat loss from the monitored ger.

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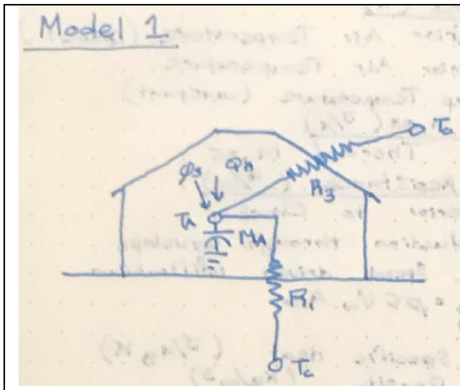
<td>
</td>
<td>Model 1 is the simplest model, accounting only for losses to outside air and to the relatively constant ground temperature</td>
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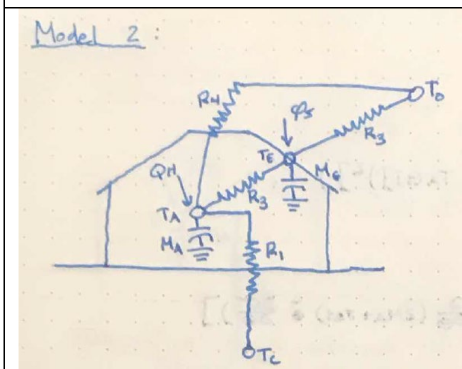
<td>
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<td>Model 2 is more complex, distinguishing the pathway through the envelope from the pathway due to air infiltration.</td>
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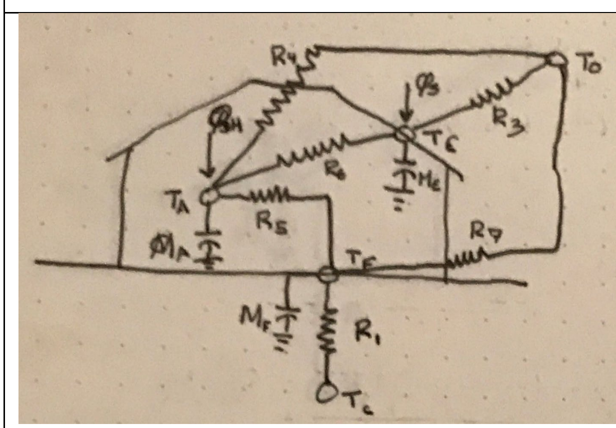
<td>
</td>
<td>Model 3 adds another set of pathways, distinguishing the edge losses of the floor from the heat going into the ground.</td>
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