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Subterraneans: A Regional Earth Dwelling for Comfort and Beauty

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SUBTERRANEANS

A REGIONAL EARTH DWELLING FOR COMFORT AND BEAUTY

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SUMMARY

Subterraneans is a study of an affordable, self-sufficient, sustainable, and dignified housing prototype for the region of Northwest Arkansas. It is a design process investigation based on the ideas of turning a local, sustainable material into affordable homes that can be built within a community of people sharing land and resources. The homes would utilize as many natural materials as possible to minimize the impact on the Earth and the cost to the owners.

Research looked at many different vernacular building precedents as well as the work done by contemporary design firms in the area of economical, low-impact, and passively temperature-controlled buildings. The design is in the form of a tube made from straight pieces of dimensional lumber aggregated into a diamond-grid. This cylindrical form allows it to be

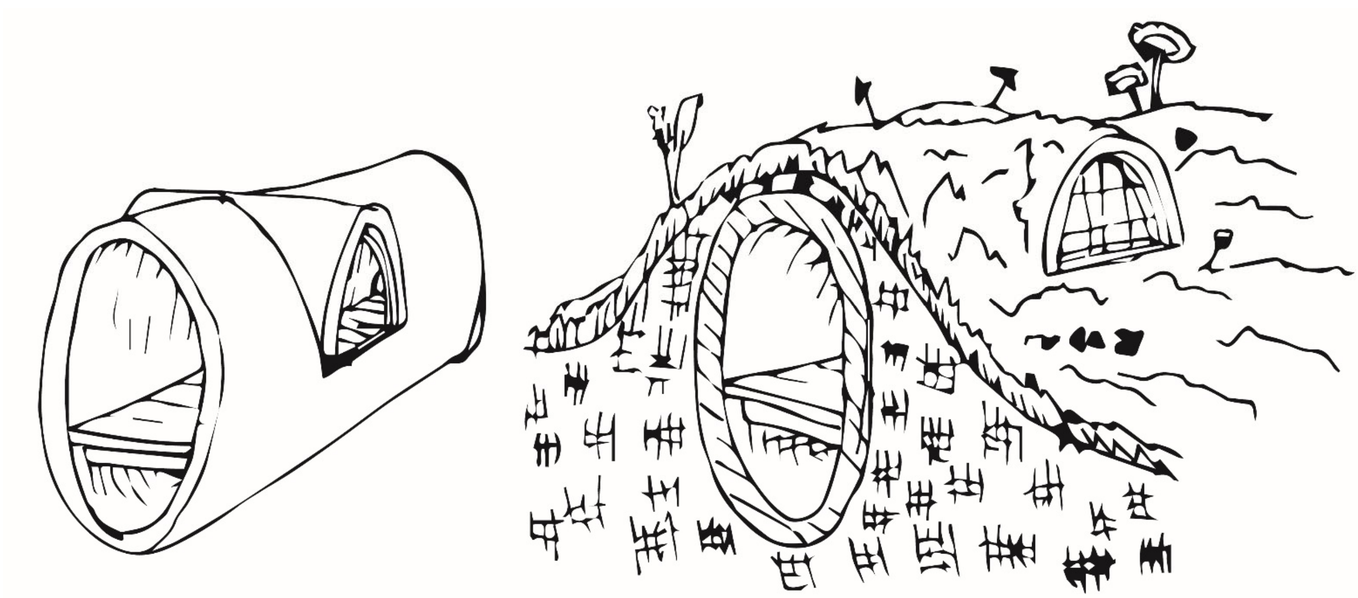
buried with a depth of soil to use the ground and vegetation as natural insulation and thermal mass while creating an effective structure to apply even pressure against the surrounding earth and water.

The various parts of the project were subjected to further research and tests to determine the overall viability of the scheme. Important aspects of the project were: structure, water repulsion, access to light and air to various benefits, its effects on the landscape, and the cost and ease with which to build.

A west-facing apartment and an east-facing window in a home. The residents had to modify the glazing to control the amount of light, examples of placeless and inconsiderate housing.

INTRODUCTION

In Northwest Arkansas there exists a row of cities, each one host to vital industries that serves the larger region. The past decade, however, has seen an alarming rise in the cost of housing to a point that the key residents in the region are uprooted and forced to move further away from their jobs. If this trend continues, the region risks economic decline. In an increasingly exorbitant housing situation where local builders thrive in profits, building egregious and placeless houses, the industrious population must seek a new form of housing: one that leverages its location to maximum effect. In a region that is at once hilly, sunny, and highly vegetated, I investigated the design for a home that can regulate temperature through the natural environment; prevailing winds, sun paths, and thermal mass from earth and vegetation all work in service of reducing energy use. Materials must be locally abundant, sustainable, and capable of being moved by one or a few people.



The search for an ideal form began with a vision of a tubular home inserted into the ground so that a contiguous surface of earth may lie on top. In some places a door or window poke through the soil covering. The initial plan was to develop an essay on material research on new ways of creating an earth shelter at low cost, however, in the months leading up to the semester of Fall 2022, I was struck with an epiphany; such a home cannot rely on assuming all aspects of its design will theoretically work as intended; It must be a proposal that tests the limits of common and affordable materials, and so I must pursue a test of physical properties.

Using basic cut lumber and treated plywood as the premise of the design at a material level, the goal of my research was realized: to test the viability of a domestic structure built of dimensional lumber in a lamella system and covered with soil and vegetation as its primary cladding and insulator. Viability will be determined by its livability, cost, and ease of construction. It must be stable to temperature, water, and wind. It must not be overly humid. It must be buildable for relatively little expense with common materials. The proposal must bear minimal maintenance costs to its owner and preserve the continuity of the landscape.

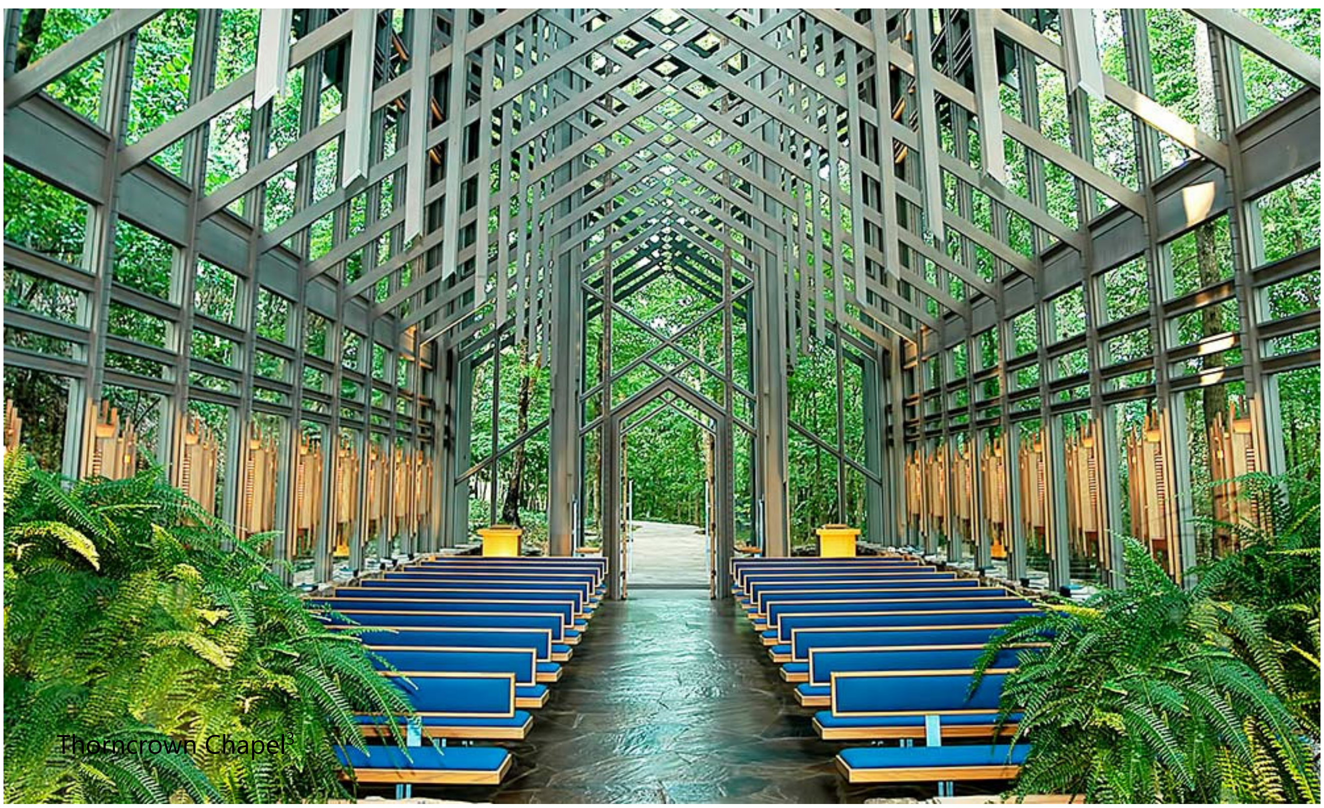
Wood Stud Foundation[1]

Hale County Animal shelter[2]

1. Robert, Whitehead. *Structures by Design: Thinking, Making, Breaking*. Routledge, 2020.
2. Andrew Freear, Elena Barthel, and Andrea Dean Oppenheimer. *Rural Studio at Twenty: Designing and Building in Hale County, Alabama.* (New York: Princeton Architectural Press, 2014.)

CHAPTER 1: ORGANIC AND VERNACULAR

An organic design here means; a building that is created using the path of least resistance. This does not mean that this building is boring or uneventful but is a product of its circumstances. Fay Jones famously designed Thorncrown chapel in such a way that its construction relied only on structural members that could be sourced nearby and hoisted and placed by two people.[3] In form, it is complementary of its wooded context. This design philosophy allows one to leverage the location, at once creating a context appropriate and economical building, and is the enemy of the placeless houses that do not respond to the environment.



Thorncrown Chapel[3]

3. Thorncrown Chapel. “About us.” Accessed November 25th, 2022

Further precedents in this area include what is called vernacular architecture, buildings that are made by those untrained in architectural practice, outside of any design profession or academia. I began looking at vernacular houses across the world, and at once identified a trend. The world over, there are vernacular homes that, using only what is literally beneath the builder's feet, the builder accomplishes a house that is at once passively stable to temperature in extreme environments and made of a skin that is simply a continuation of the surrounding earth.

In the nearly arctic tundra of Iceland, Norse settlers constructed an adaptation of their typical sod-covered longhouses, known as the turf houses of Glaumbær. They would cut blocks of earth from the ground, held together by a matrix of roots. These would be stacked in a herringbone pattern to create a structure resembling an A-frame. The homes are thick-walled and green, nestling close together to maximize use of material. They emerge from the landscape as a row of house facades built onto what resembles a small hill.[4]

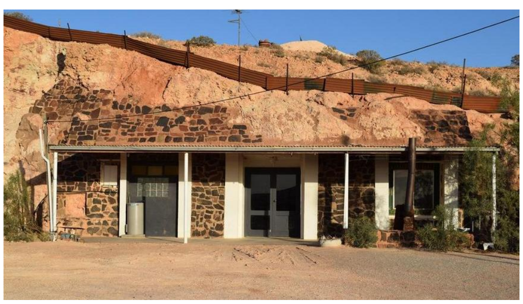
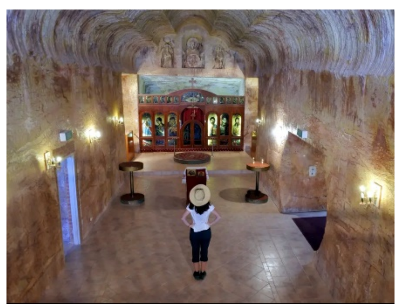
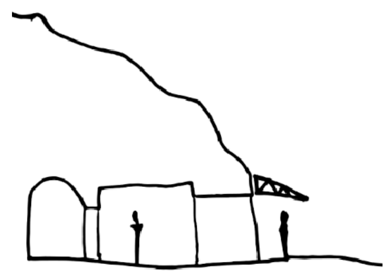
In the interior of the outback of South Australia is a town called Coober Pedy. Settlers


Glaumbær Turf Houses[4]

4. Guide to Iceland. "The Historic Glaumbær Turf Houses of North Iceland." Accessed November 25th, 2022.

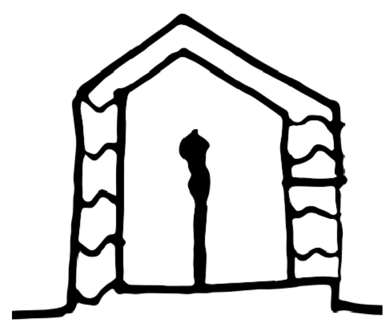
were first drawn to the area to mine opals, a business that boomed until 1916. Afterwards, left to themselves in a desert of rock and cliffs and discarded mining equipment, the settlement took an interesting shape as new homes were carved out of the rock. As this practice became a staple of new buildings, a culture surrounding tunneling emerged; for example, a common baby shower gift is your friends entering your home with jackhammers and carving a new child's room. The result is a town where windows poke through stony cliffs, the spaces nestled deep within the rock behind to protect from the heat.[5]

Pioneers in the western prairies of the United States had limited access to any timber at all. For warmth, they burned sun-dried cow feces. Their homes were made of 3-foot-thick blocks of sod, stacked in the fashion of brick courses. With similar circumstances and construction to

Above: Coober Pedy Homes and Church[5] Below: Nebraska Sod Homes[6]





5. Weller, Chris and Erin McDowell, "Inside Coober Pedy, the Australian mining town where residents live, shop, and worship underground," *Business Insider*, May 3rd, 2020.
6. Nebraska Studies. "Living in a Sod House." Accessed November 25th, 2022.

the Icelandic turf houses, they functioned much the same, providing a thermal mass as shelter from temperature, although in this case in a temperate climate. They were, however, reported to be both warm in the winter and cool in the summer due to the thickness and mass of the sod.[6]

These homes, separated by vast distances, represent the struggles of people making maximum benefit of the little that was around, and in all cases take form as substantial thermal shelters. Although there are many examples of vernacular architecture, these are chosen for the triple duty of their chosen construction: proximity to natural material and therefore **sustainable and economical materials**, thermal mass and therefore **passive user comfort**, natural cladding and therefore **harmony with the landscape**. These important principles can be used to reflect on modern design philosophies.

6. Nebraska Studies. “Living in a Sod House.”

CHAPTER 2: MODERN DESIGN PHILOSOPHY

Sustainable and Economical Materials, Passive User Comfort, and Harmony with the Landscape are each remarkable features of great buildings. Of the countless buildings on the planet, very few adhere to any two of these at once, let alone all three. Most buildings, we can assume, achieve economy of material very easily (though not necessarily sustainable). Those prioritizing passive user comfort and harmony with the landscape are very seldom built most economically, and understandably so; such things are most often achieved by hiring a designer who has access to and willingness to implement more expensive materials. To understand why these are not ubiquitous features across all buildings, we must study the design philosophies of three different design offices who have a relationship with these principles.

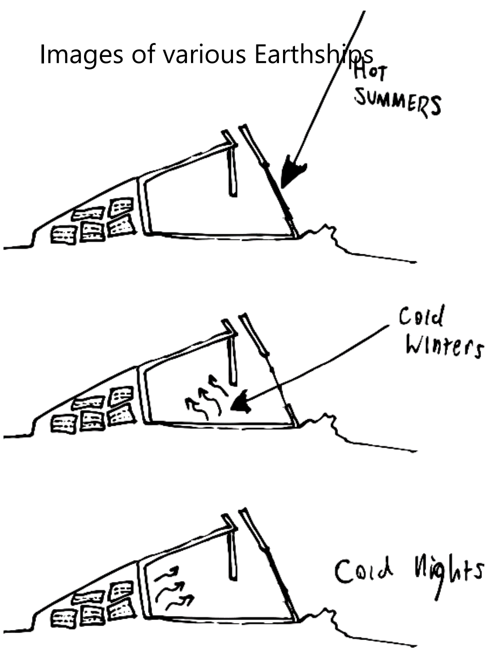
An influential designer in the field of earth sheltered homes is Michael Reynolds, known for designing Earthships, a technology that can be used anywhere on the globe, he claims. Earthships are user-built homes predicated on the principles of passive cooling and heating utilizing common byproducts of modern life. Used tires are packed with earth and stacked into a berm comprising the north face of the building. The south wall is a skyward row of operable windows, behind it a greenhouse sunroom and then a wall acting as a thermal barrier between the sunroom and the living spaces. That wall and the flanking walls on the east and west are made of stacked cans or bottles and the gaps filled in with concrete. The roof is rough-sawn lumber covered with a simple membrane and a shallow layer of soil to weigh it down.[7]

7. Reynolds, Michael. *Earthship Volume I: How to Build your Own*. Taos: Solar Survival Architecture, 1990.

In theory, the Earthship works by accepting direct sunlight in the winter, transferring the heat in the space to the compacted earth berm, and releasing the heat at night. In the summer, the glazing is shielded, and roof openings vent warm air. The earth berm acts as a thermal mass would in an adobe house by drawing in warmth during the day to be exuded in the cold night.

In practice, no Earthship functions within a comfortable temperature range year-round by passive system alone; without a supplemental active temperature control, winter temperatures stabilize around 60 degrees Fahrenheit, 80 degrees in the summer. Constructing an Earthship without experienced help is backbreaking labor, involving many hours of packing tires. Cleaning bottles and cans uses lots of water. Worst of all, accessing tires, cans, and bottles requires removing materials from the recycling stream and transporting them long distances, and in the end, the structure is 40% concrete. All these things considered, an Earthship can cost upwards of

Images of various Earthships



8. Prinz, Rachel Preston. *Hacking the Earthship: in Search of an Earth-Shelter that Works for Everybody*. Albuquerque: Archinia Press, 2015.

$200 a square foot.

The ambition of Michael Reynolds to use only those things people throw away is a solution antithetical to what is called the Cradle-to-Cradle design model, whereby the goods consumed by society are inherently capable of being returned to usable state. Removing tires, bottles, and cans to be used in construction renders lower quality buildings with less incentive to find a better use for them. A sustainable design uses materials that are in support of a supply chain that creates sustainable products. For instance, these products could be locally sourced lumber, a carbon sequestering material, meaning their use and maintenance helps to remove excess carbon from the environment.

In Alabama, the nonprofit Rural Studio works with Auburn University students to create unique, identifiable homes and public buildings for communities in need. Recognizing the opportunity to use local lumber for sustainability and support for local economy, nearly all their built work involves dimensional lumber as the structural unit.[2] The result is a landscape of very economical and unique buildings and homes that instill pride in the community.

2. Freear, Barthel, Oppenheimer. *Rural Studio*

One civic building of particular interest is the Hale County Animal Shelter, a larger work that implements the Zollinger Lamella roof, an uncommon diagrid structure built of straight lumber aggregated into a half-tube. Rural Studio proved the effectiveness of the lamella roof and its economy and speed to build, and at the same time provided a facility for a needed service. The open canopy lamella roof encompasses all outdoor and indoor program underneath, and the air space between the conditioned and unconditioned space is a breezeway for passive ventilation.[2] This project, among others, is indicative that beginning from an organic, location-based blueprint and allowing strategies of passive temperature control to follow

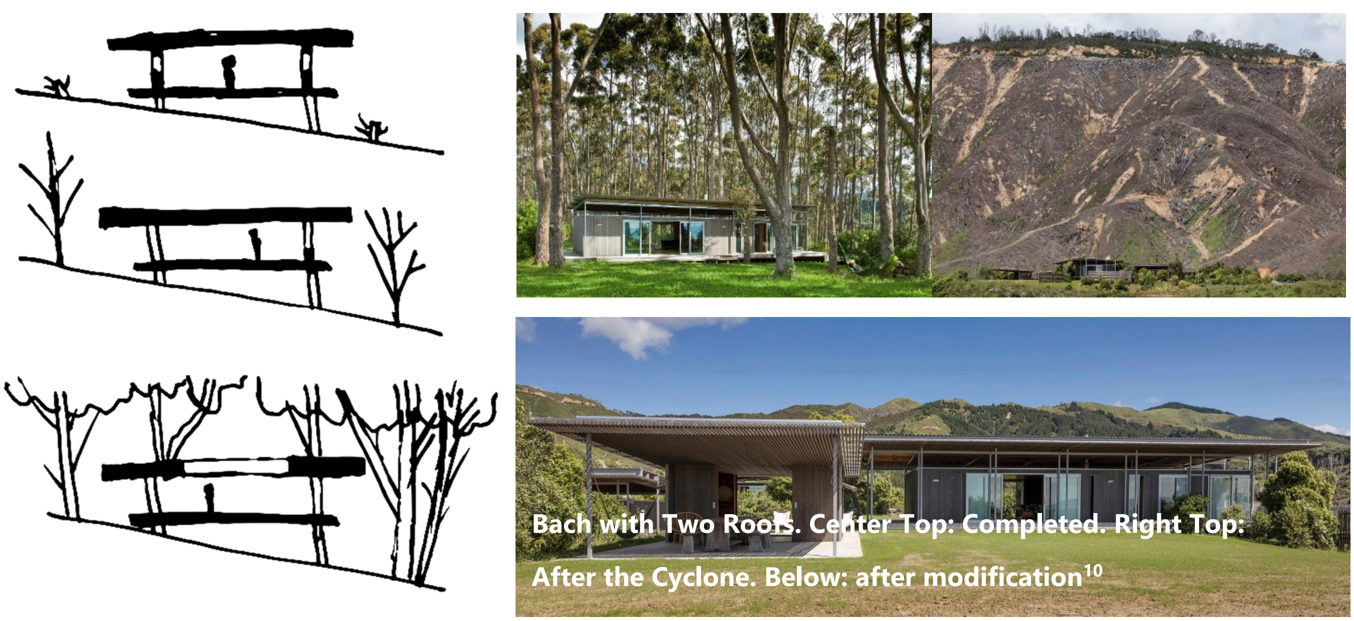
Hale County Animal Shelter, Left: Detail. Right, above: Under Construction. Right: Below Near Complete[2]

2. Freear, Barthel, Oppenheimer. *Rural Studio*

naturally is a much more effective strategy than assuming a passive temperature strategy and applying it everywhere.

In 2019, I attended a lecture given by a firm from Nelson, New Zealand. Jeremy Smith, the lecturer, described the work his firm had done on a house that was built into a eucalyptus forest, called Bach with Two Roofs. At its initial completion in 2012, the home was in a symbiotic relationship with the forest, accepting shade and cool air from the surrounding plants and trees. In 2014, a cyclone cleared the landscape. The designers retrofitted the home with new facilities and shading devices to rediscover the privacy that once was provided by the landscape. These devices were attached in a way that they could be gradually removed from the house, and this way it would anticipate the return of the forest.[9]

Irving-Smith in Nelson, New Zealand pays close attention to the landscape, and in New Zealand, the landscape is on the mend from centuries of European settler clear-cutting. Bach



Bach with Two Roofs. Center Top: Completed. Right Top: After the Cyclone. Below: after modification[10]

9. Smith, Jeremy. "Soft Architecture: Is Being Finished, Finished?" Lecture Presented in Schollmier Hall, 205. February 11th, 2019.
10. Archello. “Bach with Two Roofs.” Accessed November 26th, 2022.

with Two Roofs, as well as other homes by Irving-Smith, are in harmony with the landscape, not in domination of it. Any building that accepts native plants to grow to maturity unopposed will reap many benefits. To the landscape, habitats for animals are fostered. For the owner, vegetation supports user comfort by providing cooling in the summer, while still allowing passive warming by the sun in the winter.

To achieve a home fabricated from local, sustainable materials that harmonizes with the landscape and provides user comfort through passive systems, the scheme must follow the natural form assumed by what is the most abundant and accessible construction material. Passive systems come from understanding the landscape and arranging the structural system to best fit to forming the harmonious relationship.

CHAPTER 3: HUMIDITY

In June of 2022, I began construction of a small-scale prototype to test the long-term effects of soil, vegetation, and moisture on a wooden lamella. The structure was a balsawood lamella constructed, at scale, as dimensional 2x6 lumber. The foundation was made of concrete footing with stud walls, 2x6 decking, and 1/16” balsawood sheets as plywood cladding and decking. Walls to close the structure were added with an operable window and door. Following Hale County Animal Shelter as a precedent, the wood cladding was followed by an impermeable

Prototype Under Construction

membrane layer, in this case a repurposed sheet of plastic, and sheets of aluminum. The structure was finished in mid-July. It was placed into a tub and covered with layers of soil with miscellaneous seeds from flowers to accelerate growth on the structure. In the late summer, as it sprouted, the interior was carefully inspected after rains for leaking and moisture damage. After the first rain a sill was added to the bottom of the door, as some water began to collect there.

By mid August, the floor of the prototype had turned the same gray as the exposed balsa wood where it had sustained water penetration from the door. After this time, the window and

Prototype from July to September

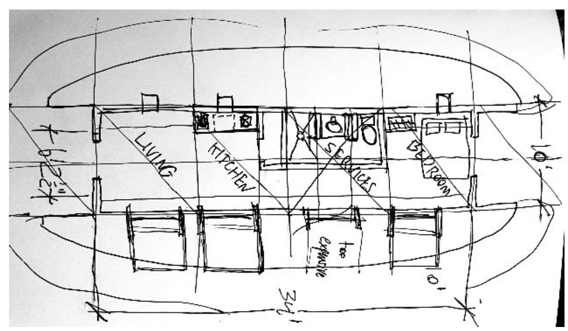
door of the home were left open for ventilation to prevent the further growth of what I assume to be mold. Even with the window and door open, no new water penetration occured in any place of the structure. Photographs were taken to document changes in the foliage growth and to identify any leaking. As of the end of November, the grass and flowers are browned and wilted in the cold air. The interior has not changed color or showed any signs of leaking; it seems ventilation was necessary to prevent humidity from affecting the structure further.

Prototype from October to November

CHAPTER 4: LIGHT AND AIR

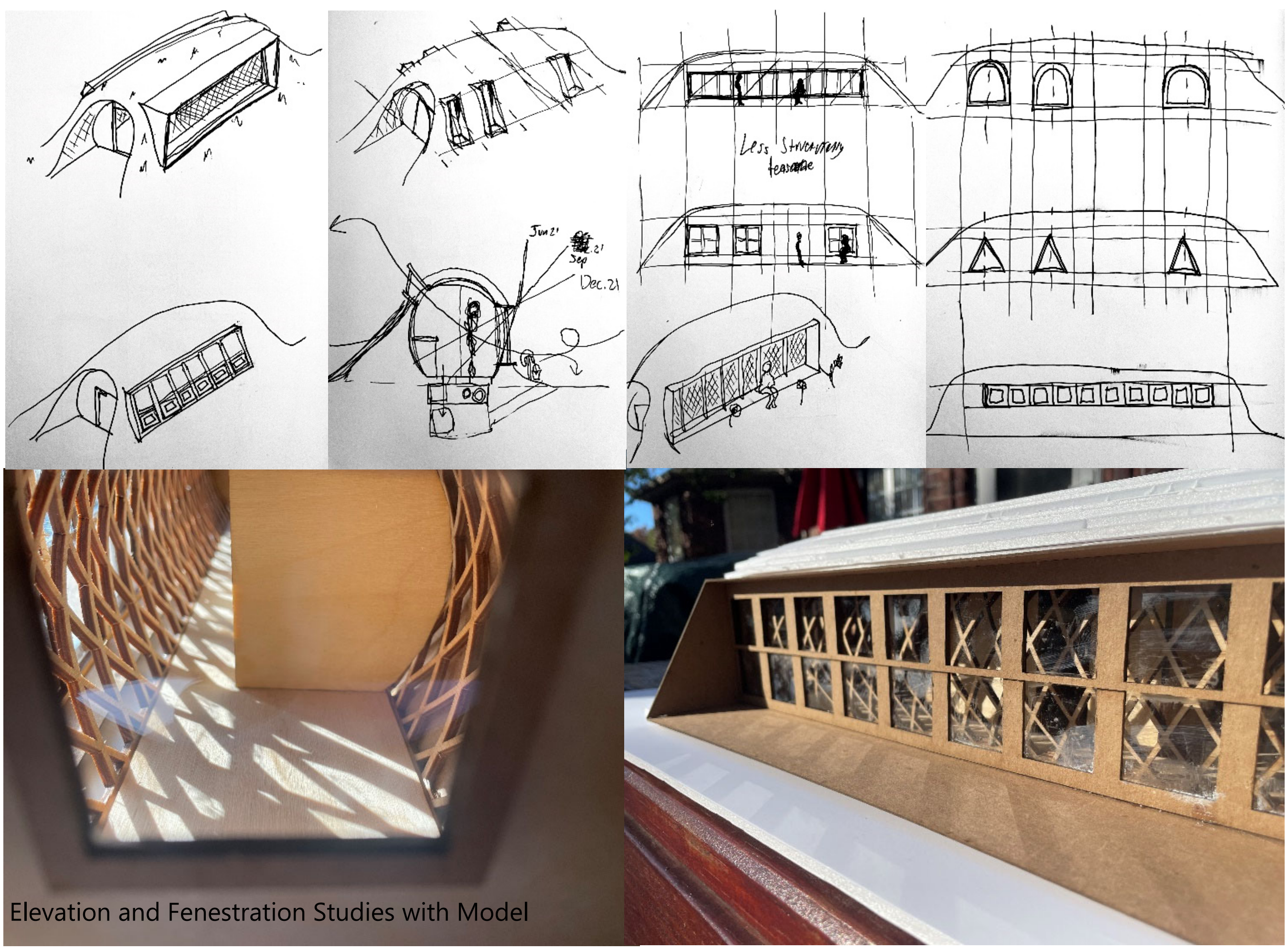
The task was set to develop the system as a real space. A very small and basic floor plan for a home was layed out within the structural shell. Minimal windows were applied to the exterior to mitigate as much heat as possible. At this time, it was explored that perhaps the home should be buried as deeply into a slope as possible, so as to act almost as a bunker for the occupant. In this way it would function more like a traditional sod house, regulating temperature by thermal mass.

This project became not be about making a typical earth-shelter, but one that has the unique benefit of opening south to the sun, allowing light and air into the space in a way that



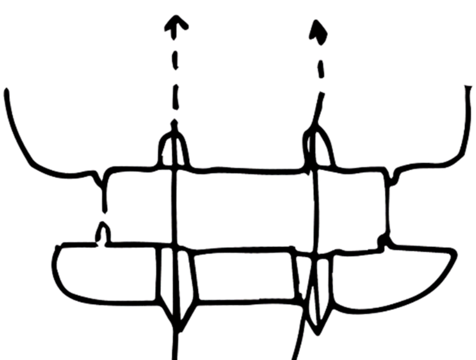
Plan and Section Iteration, October 5th

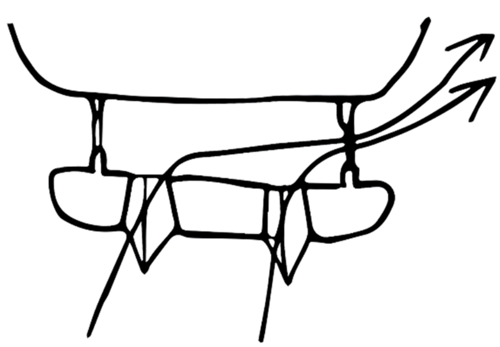
benefits the user from a perspective of temperature regulation. Of the many different proposed strategies, the best one offered a large row of continous glazing to the south. The embrasure of the window piercing the earth would give it the thickness to block direct light in the hotter months, while its height would work to maximum benefit in the winter, sun pouring deeply into the space. The exterior of the window could also be occupied, providing a deep and wide porch area. Models were constructed to observe lighting, and these found the large glazing strategy to be both favorable for comfort and beautiful. Taking full advantage of large glazing means

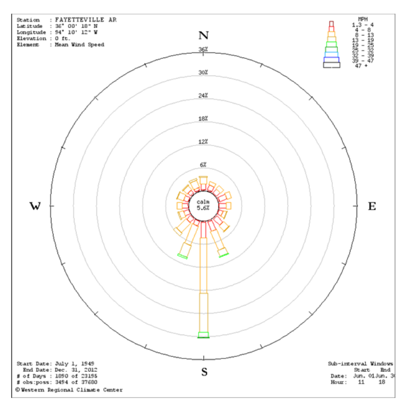


Elevation and Fenestration Studies with Model understanding how it can utilize the wind to aid temperature control in the summer. The prevailing winds in Northwest Arkansas are most strong from the south in the hotter months,[11] allowing the south windows to be used to for drawing in air. For ventilating the wind away, smaller openings should be made opposite to the larger intake windows. This gives the wind a place to exhaust, however it must increase in velocity as it moves through the space for the volume of air leaving to match the volume entering. This is an effect in fluid dynamics called Bernoulli’s Principle, and it helps in making passive ventilation more effective.

Models and diagrams were made to observe the reaction of air through the house. One model was the prototype with windows cutting through the earth to make a direct path for the air. The other model added no new windows but assumed that the air would vent out through the door and the window opposite from it. Access to the wind tunnel was asked for, however I asked too late. Analysis instead came from placing the models outside on a windy day and feeling the movement of the air with my fingers. The model with openings cutting directly to the north was less effective than the second. The air, it seems, found easier path with the shorter







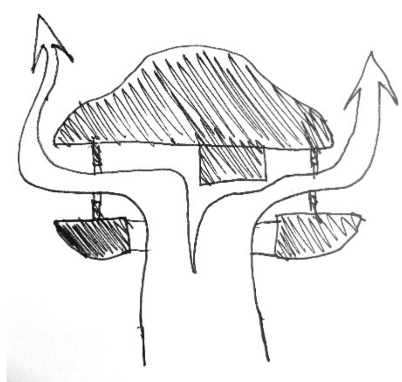
Wind Studies and Wind Rose[11]

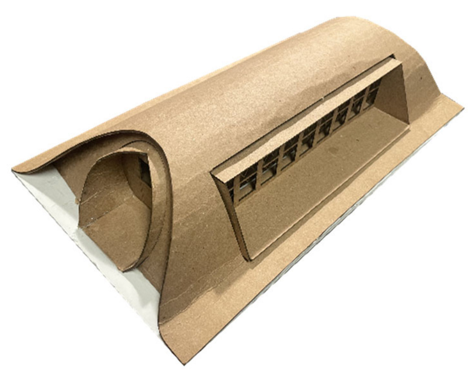
11. Wind Rose Climatology Center “Fayetteville.” Accessed November 26th, 2022.

distance in the model that vented out the sides. The shorter but less direct path has another very strong advantage; such paths create wind eddies that increase moving air contact with the walls of the structure, more effectively drawing away heat. This also avoids puncturing the moisture envelope on the north side.

Building the home into a southward incline has huge benefits to the home for shedding water, solar access, and lessening the amount of soil that needs to be moved for the northern berm of soil coverage to work effectively in stabilizing the temperature. The passive strategies in the winter depend on this, as the direct winter sunlight into the space warms the walls, that heat is transferred into the adjacent soil, allowing that warmth to radiate back into the home at night. In the summer, the temperature is kept cooler by the berm acting as a heat sink, as it is close to the normalized temperatures of the earth. The direct sunlight is limited in these months by the thick window embrasure. Additional cooling comes from opening the south windows, allowing excess warmth in the walls to be drawn away as it is forced through the secondary openings.

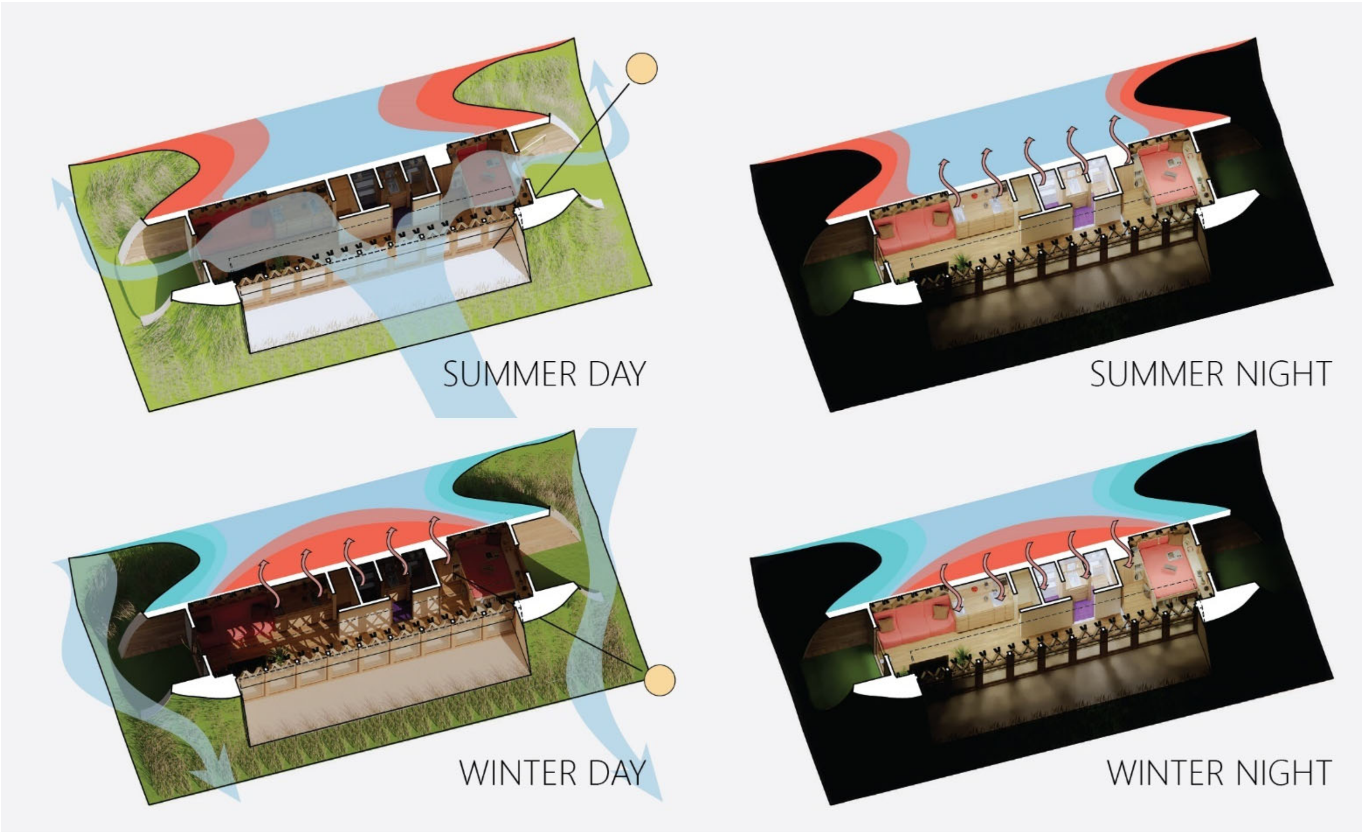
The presence of vegetation is certainly good for any building, as in the summer shading





Wind Study Models

and transpiration from the leaves cools the surrounding air. Sunlight is not blocked in the winter, as by then trees have lost their leaves. This home maximizes the potential for plant life by not depriving any area for their growth.

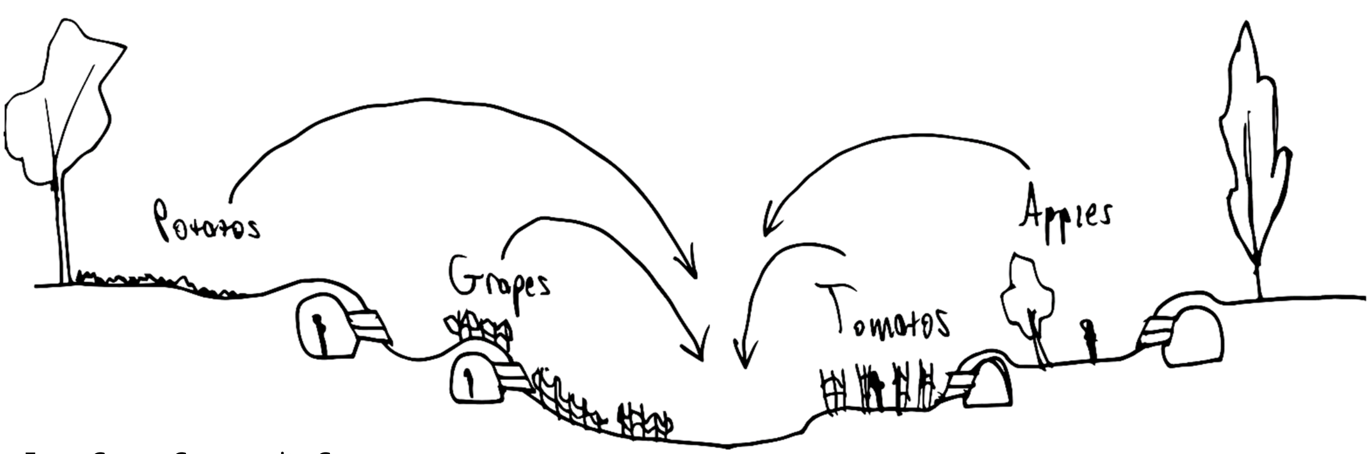


Passive Temperature Control Diagrams

CHAPTER 5: LANDSCAPE

The appeal of this home is to those who can't afford a typical permanent living residence, providing an economical alternative that allows them to rely on their own industriousness and community-mindedness to execute construction of what is ultimately their own. In a few different scenarios, we can imagine a collection of younger prospective homebuyers opting to band together, finding a plot of land to share, and inserting homes into the landscape. These ideas conjur images of people looking for an alternative lifestyle finding a place to be entirely self-sufficient, but this is not necessarily the case. A few different landscape conditions were explored; people looking to create a farming co-op in a nearby rural area, or working men and women simply converting an urban infill lot into housing that is at once dense but also abundantly green.

Part of the inspiration for exploring a subterranean home is my desire to see this area that I've grown up in to remain as green as possible. Since my childhood, I've witnessed the



Farm Co-op Community Concept

intense urbanization of my hometown of Springdale, sometimes for good, often for bad. Urban sprawl, new big-box stores, and houses constructed for a dime-a-dozen are a huge part of what is wrong with modern urban development. In some places, however, like downtown Springdale and Fayetteville, some positive changes are in effect: new public spaces, new parks, new paths for pedestrians and cyclists. These implementations increase interest to town centers, creating more favor to focus our urban development on culturally significant places. In support of this vision, the sites I spent most time developing as potential places for my prototype were those closer to downtowns and businesses rather than typical suburban lots.

The first site was on the Greenway bike trail in Springdale, just a five-minute walk from the town square. It was chosen for its slight grade change, sloping towards the very active and popular Spring Creek. It's a wide and clear space besides, with excellent drainage. Land like this in Springdale is often used for agriculture, and so it would be here. The owners could design their plot of the property to suite their own needs, allowing them to capitalize on their land through cultivation of a garden or an orchard, which would otherwise be wasted area if the land

Springdale Site at Spring Creek and Concept Plan were subdivided for typical houses. This land, however, poses a new design challenge; its slope faces to the north. This is an unfavorable condition to the protype, because it requires more earth cutting to make the design function. This implies that there should perhaps be multiple prototypes to account for different orientations to solve this issue.

In Fayetteville, there is an infill lot sloping to the south on the edge of Mount Sequoyah, just east of downtown. It is a smaller lot with many good aspects: its adjacency to businesses and other homes, its openness to views and light, steep grade change, excellent drainage, and potential for vegetation. For this site, three proposed houses are set into the slope, which is angled slightly to the southwest. The homes here do not garden for food, but rather let native grasses and vegetation overtake the lawn. This way, their presence on the site turns the

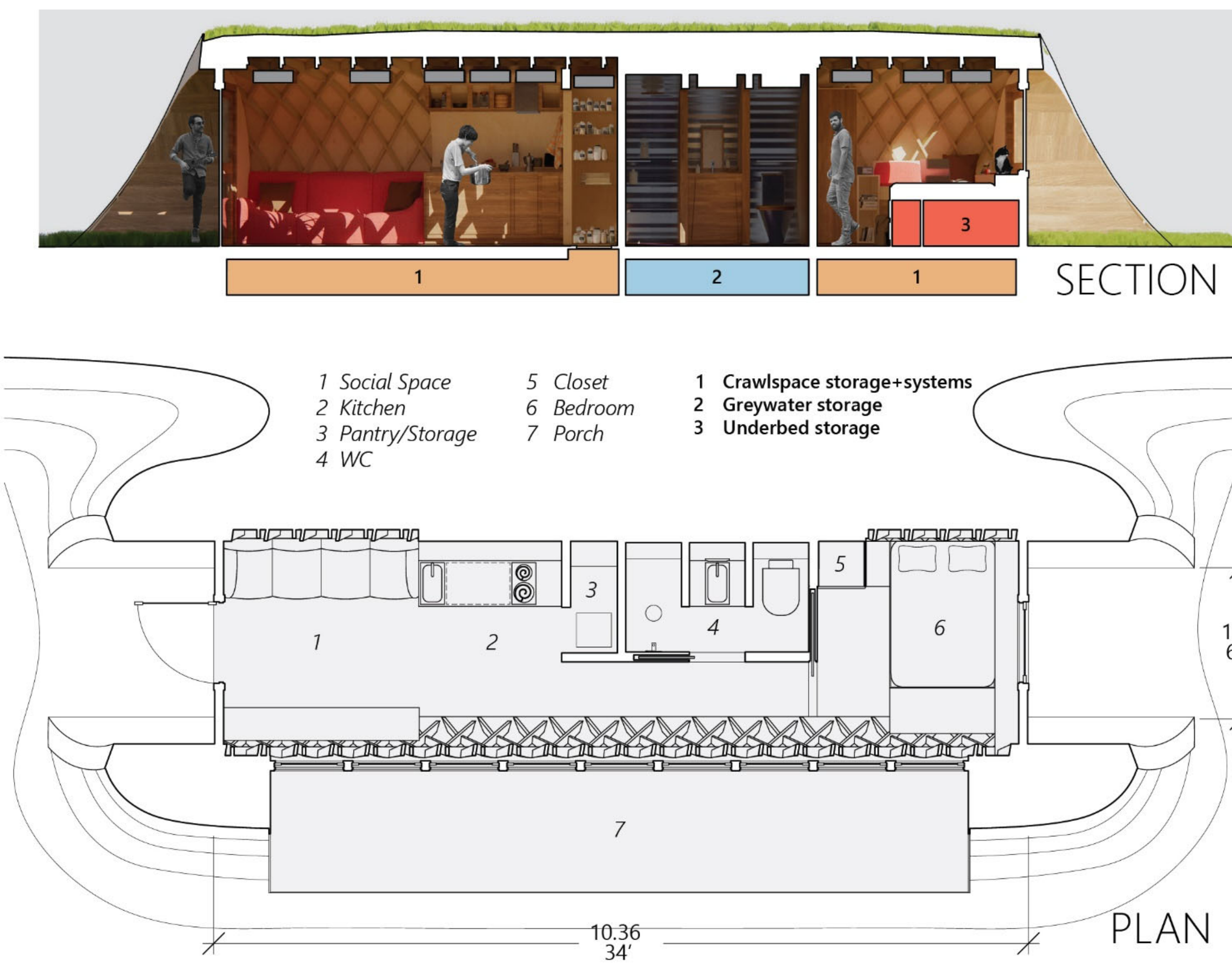
Concept Diagram for Urban Farm Co-op

monoculture grass hill into a biodiverse prairie, the homes themselves taking away no footprint for smaller plants and animals. The occupants, meanwhile, enjoy the spacious and healthy landscape. Because of their demand for housing was fulfilled in a way that promotes biodiversity and increased urban density, somewhere else in Fayetteville trees and animals are not subjected to further spread of suburban development.

In the landscape at large, there are plenty of suitable sites for the prototype: an urban infill lot sloping to the south. The desirability of the lot to development depends on its adjacency to businesses, however, and given the state of disparagement between workforce wages and cost of housing and transportation, it is most important for low wage earners to

Fayetteville Infill Site, Concepts and Site Photographs capitalize on density to save on costs. This home has the pertinent advantage of being potentially denser than typical housing while maintaining the green space that is important to this region's urban areas.

To broaden the reach and potential of this prototype, it needs further research into how to adapt the fenestration to orientations other than directly south. Its dependence on following the slope of the earth means it is restricted to being built in whatever orientation the grade change on any particular site happens to be.



CHAPTER 6: STRUCTURE

To create a home accessible to the lowest earning person possible, the home must be designed thusly: to be made of the most common materials, to function as effectively as possible with these materials, to be as economical and fast as possible in construction with these materials. Cost comes down to, inevitably, what it costs to create, ship, transfer, handle, cut, and use building materials. Dimensional lumber fits this criteria best for a home and, in this region especially, makes the most sense for a house. Labor, however, is the most costly part of creating a building, and has a directly proportional relationship to the cost of materials. The rule of thumb is to multiply material cost by two to calculate labor cost. The goal for a wood Zollinger lamella, then, is to minimize all costs associated with this area, by providing an effective and economical structure that fulfills all demands. Going further to reduce costs, the homeowner would build his or her own home. Can this home be built so easily?

For an underground house, how do we maximize the amount of natural coverage without compromising the simple structure? It is important that we investigate the ergonomics and

Construction of Test Models: Steaming, Shaping, Gluing practicality of building it. As part of this, I built a series of scale models to load in different ways. Depending on the model's behavior when loading, and how much weight could be held, we could determine if this was an appropriate form for the task of holding soil. One concern was the structure's inherent curving underneath itself, an entirely unique form for a lamella. The explanation is, of course, that this is the shape best suited for counteracting the multidirectional forces associated with subsurface construction. The convex shape also helps to shed away moisture.

To test many different models, it was priority to construct many small models at once. For testing I built a few identical models to load. The baseline test loaded the model directly from the top. The second test would load the model from the top with sandbags to buttress the underneath areas where it curved, as would the earth in real life. The third would be an asymmetrical loading to survey how it would deflect under uneven loads.

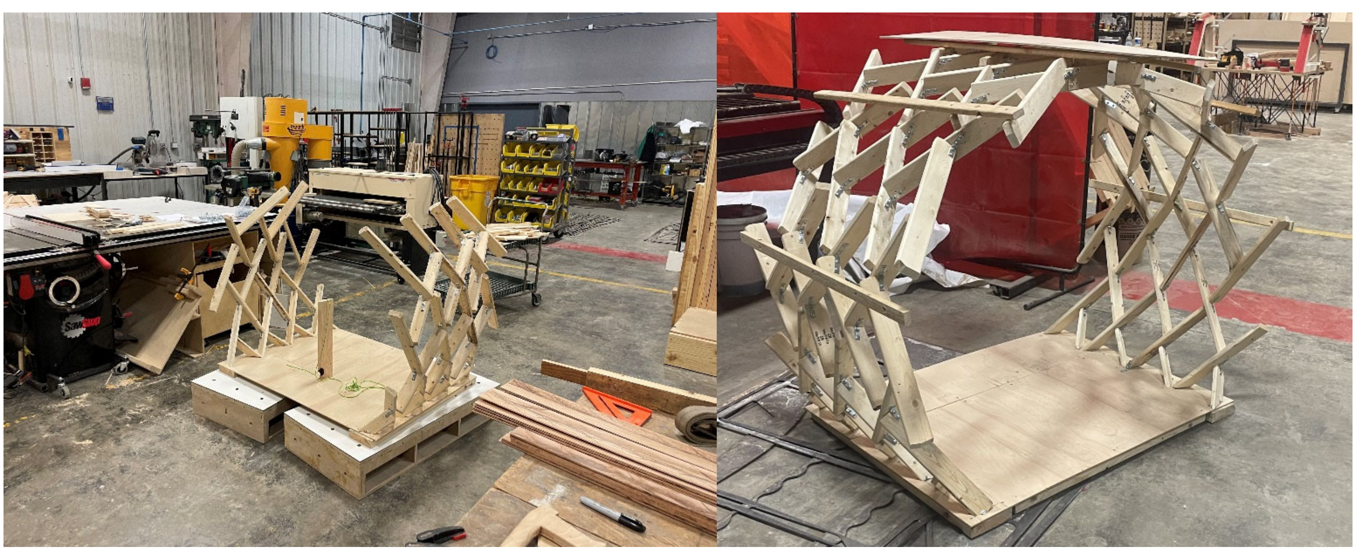
In creating the scale models for testing, it was deemed nonviable to 3d print, as at scale to fit the printer beds the plastic filament couldn't create members small enough to reflect an accurate simulation. Resin printing failed as well for similar reasons. The models were ultimately


Left to right: test 1, test 2, test 3

created at ½”=1’ or 1:24 scale by lasercutting a diagrid out of 1/8” plywood that was steamed and bent around a formwork and then clamped into place, later glued to a wooden base. A layer of 1/16” chipboard was used to simulate the rigidity of the plywood cladding.

The results were very clear; loading from the top created the most deflection and held the least amount of weight, 7 bricks. When buttressed symmetrically the load taken was a startling 14 bricks. At 4.5 pounds each, that equated to to about 63 pounds. The test was ended before failure, however extreme deflection started after 6 bricks, or 27 pounds. The asymmetrically loaded test was partially buttressed against the back of a desk, with a sandbag acting as a buffer that would swell against the side of the structure as it took part of the load. The total load recieved was 18 bricks, 81 pounds, at which point it was too unstable to continue loading. 10 bricks, or 45 pounds, were needed for deflection to occur.

The robustness and flexibility of the models is partly attributable to them being a continuous surface of curved plywood. This, unfortunately, is not an accurate representation of the stick built system. A new model was made for further study at 1:2 scale, a 3’ long, 4’ 6” wide,



The structural model before and after completion. A length of string the exact radius of the structure was used to guide construction.

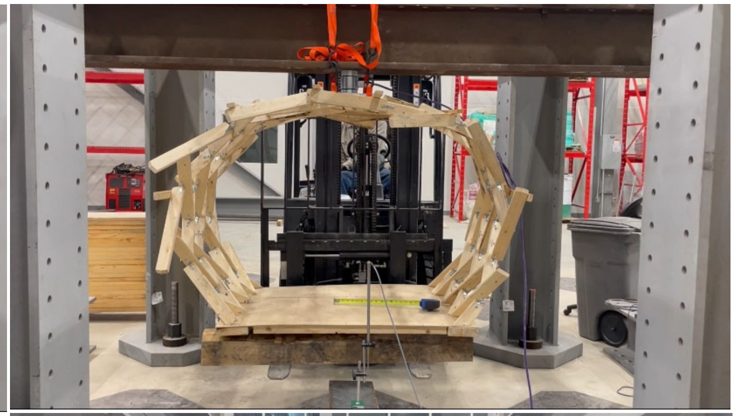
3’ 6” tall section of a lamella using 1x3 dimensional furrings as structural members. Testing was conducted at the CEREC lab, where a forklift was employed with sensors for force and displacement to measure the pound force as the the forklift lifted the structure into a beam. The maximum weight held before failure was 179 lbs. The points of failure were very telling; lower quality pieces split, the metal connections (which were non-standard) twisted and warped. The points of failure indicate that there were areas of lower craft compared to others, where the joints were not flush, and load was not transfered directly.

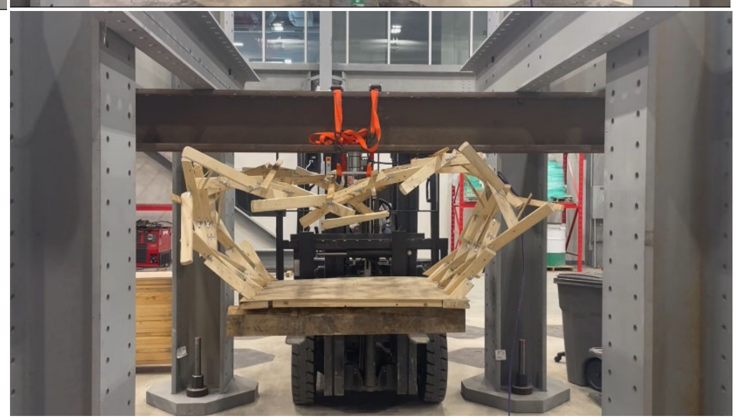
This has implications for how the building should actually be constructed, as in this case it was made without predrilled holes or centering. Typical examples of Zollinger lamella structures precisely predrill the holes in the structural members before assembly and then use centering to further ensure tight and accurate contact between members as well as an overall aligned geometry. The loading process as well was not indicative of how the home would be; the near completely circular profile is a consequence of anticipating loads from multiple directions as the

Model during load testing and structural failure points closeup

pressure is applied evenly by the ground. There is also the notable lack of sheathing around the structure, which would further strengthen the lamella armature to loads. Some addtional furrings were added to the outside before loading to simulate the effect of plywood cladding. The areas that were not reinforced in this way were significant points of failure.

Extrapolating the results of the 1:24 scale load tests to the 1:2 scale load test, the structure would hold a much higher amount of load if buttressed by the earth than if it were a point load, likely more than twice as much. Hypothetically, this half scale structural section is 1/8 the volume and mass as at full scale, and therefore can sustain ¼ the force as the full scale counterpart (not 1/8 the strength due to the square-cube law, which states that the sustained force is proportional to the surface area, not volume). This, and the fact that the small scale model held 7/18s as much weight when point-loaded rather than buttressed, gives an estimated strength of 1,841 lbs of force sustainable for every 6 feet (179 lbs*4*18/7) or 306 lbs per linear foot.





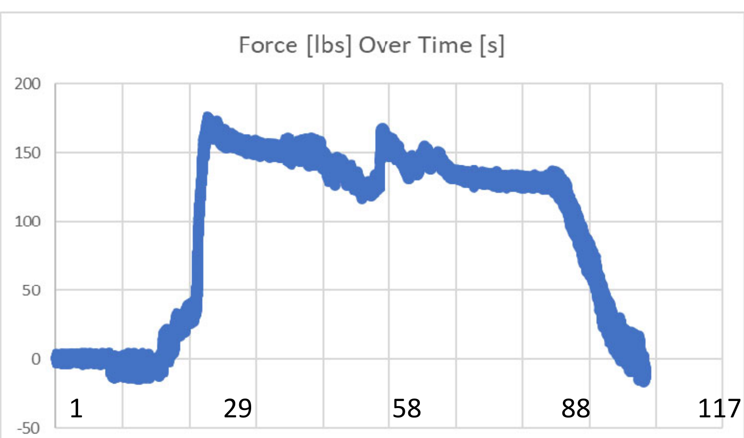
Top left: immediately before failure

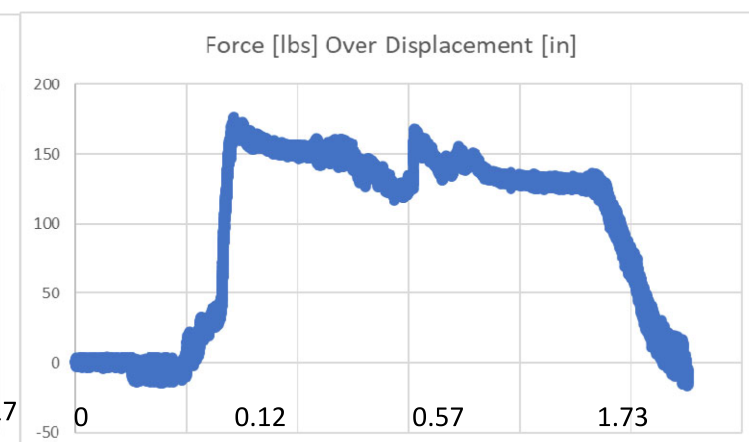
Top right: immediately after failure

Middle right: testing complete

Bottom left: a graph of force in kips (1000 lb forces) over time (s)

Bottom right: kips vs displacement in mm (movement of forks), displacement probe maxed out partway through the test

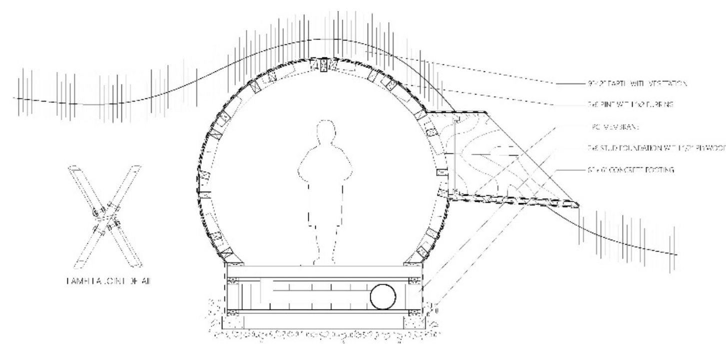




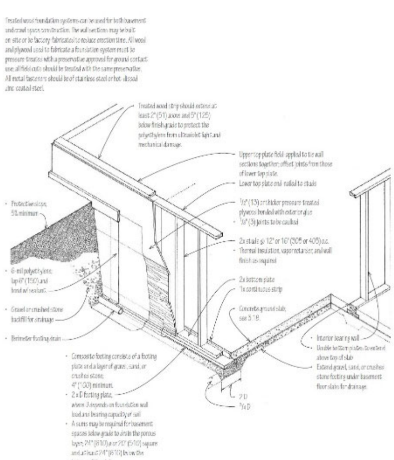
CHAPTER 7: ENVELOPE AND COSTS

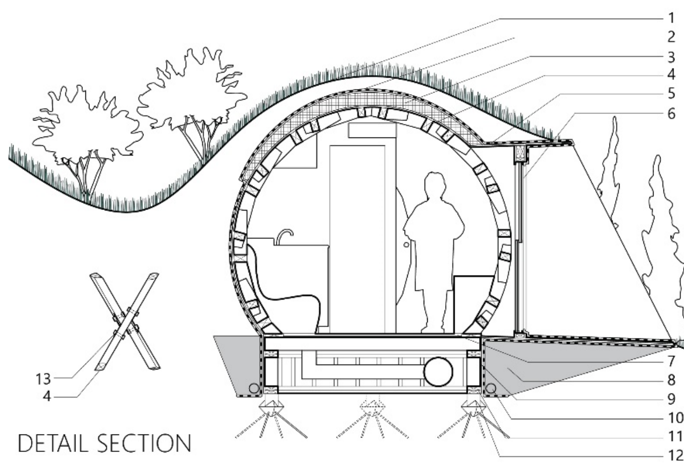
There is a huge design challenge in this project, and that is the question of water. Initial studies into details for how to sheath the curving structure indicated that for the question of ease of building, the sheathing material might be a collection of straight members in aggregation. This would be right beneath an impermeable wrap layer after which it would be clad with corrugated steel sheets in an arrangement more typical for cladding above-ground. For cost and labor, however, it is better that the home be clad in curved plywood sheets and then a layer of thermoplastic polyolefin, or TPO, an inexpensive rubber roofing material. The TPO, as well as the house's curving geometry, are likely more than enough to repell standing water or water penetration. This is based on existing wood structures that are graded for underground use: wood stud walls used as foundations.

Left: Wood foundations Right: Detail sections



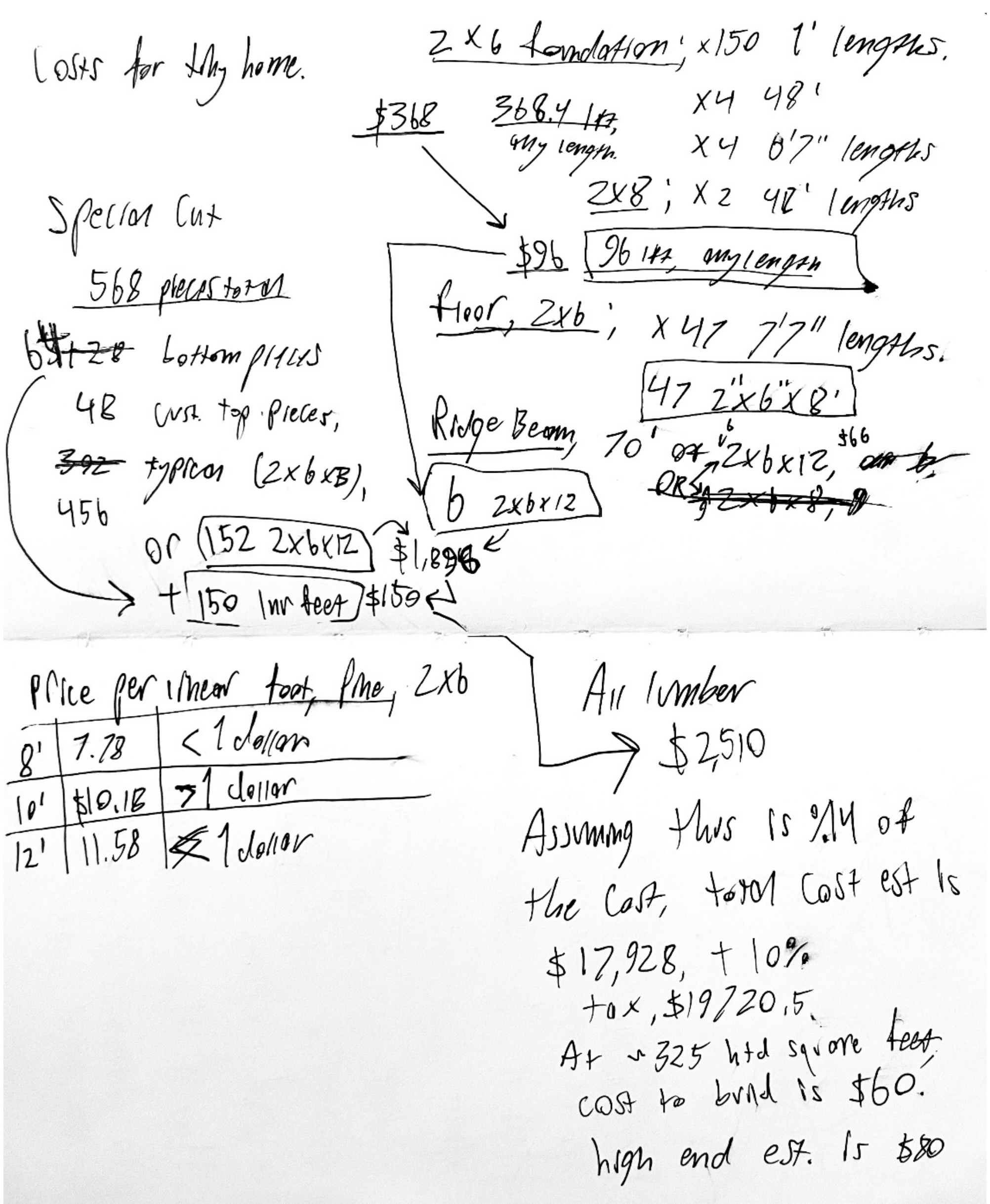
SECTION DETAIL 1/2"=1'





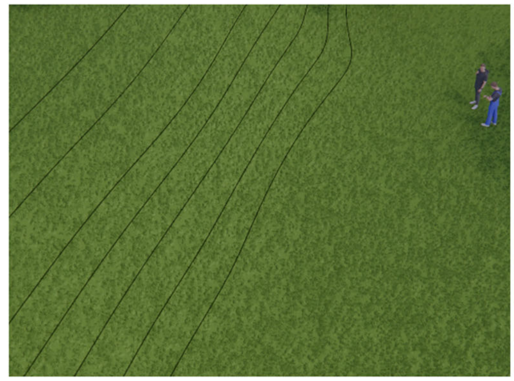
1 Foliage+earth covering and berm
2 Impermeable membrane
3 Block insulation
4 Special cut lumber, 2x6
5 Curved plywood
6 Double-hung south windows, 36x60
7 Wood finish on plywood decking
8 Gravel for drainage
9 Treated plywood
10 Footing drain pipe
11 Wood foundation wall, 2x6
12 Diamond pin foundation
13 Steel plate with threaded bolt connections

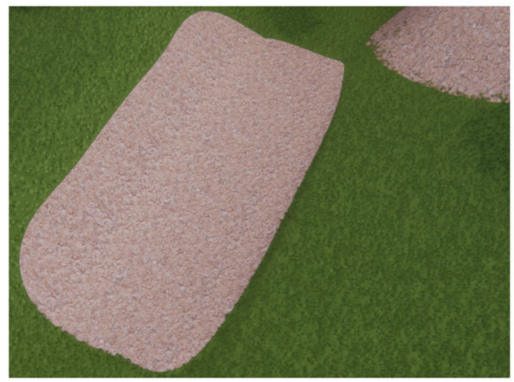
The cost to build the completed structure is surprisingly low, and by using this cost we can extrapolate to the total cost to construct. Using lumber prices frome Lowes.com, the total cost to build the structure is approximately $2,510. This is an astoundingly low number. Assuming that this represents only 14% of the total material cost, that means that at a total perimeter square footage of 325, this home is buildable for about $60 a square foot, assuming that the labor is all done by the owner and/or pro bono help.

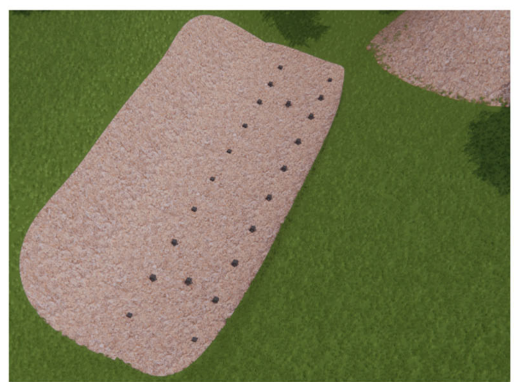


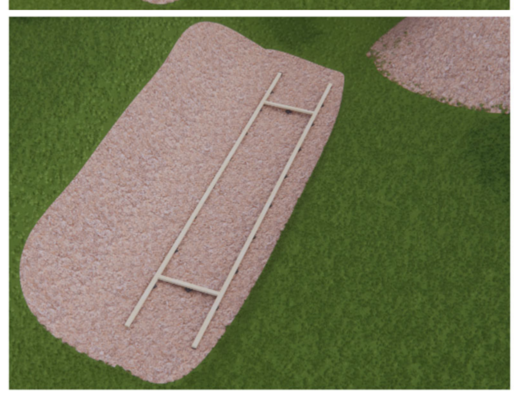
CHAPTER 8: MEANINGS

Across each dimension of the project, every question answered is 10 more asked. Sunlight, wind, thermal mass, and plants help control the temperature across the seasons; how well does the natural ventilation and sunlight do this? To what degree do they need help from active systems? How do these effects change over time? Ventilation can help control humidity; how effective would an active system vs passive be in controlling humidity? The structure can be built very quickly with common materials. How quickly can someone build it? How much weight can it actually hold? Will it perform as expected at scale against hydrostatic forces? The cost of the structure is very low; how much would the rest of the



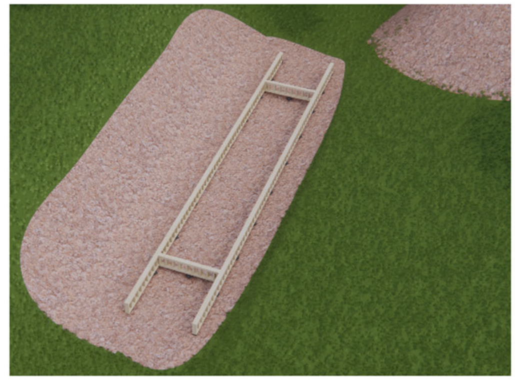


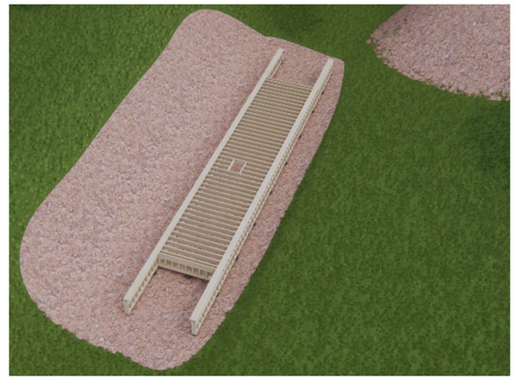


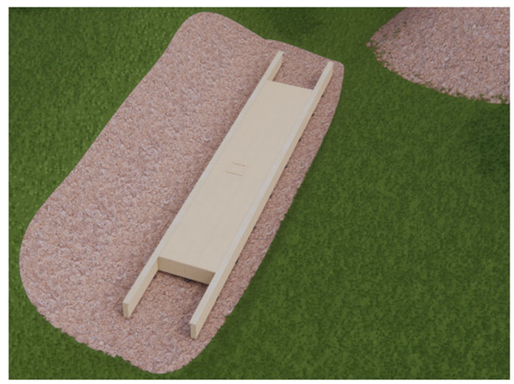


home cost? Can the ground be excavated without use of machines? The prototype is capable of utilizing southern sun for warmth in the winter and wind for cooling in the summer based on a specific orientation. How many sites could it be feasibly built on this way? How could it be modified for other orientations?

It is unfortunate for me to not have concrete answers, however these can only be learned by conducting empirical research on the prototype at full scale. I hope to succeed in this objective one day. The cost of the prototype and effort needed to build it is not daunting, but rather the cost of land in the region. What has been learned in this excercise of study and experimentation, however, has been valuable and inspiring. It instills confidence that this prototype is feasible, and an organic use of material and land for the making of a better kind of home.

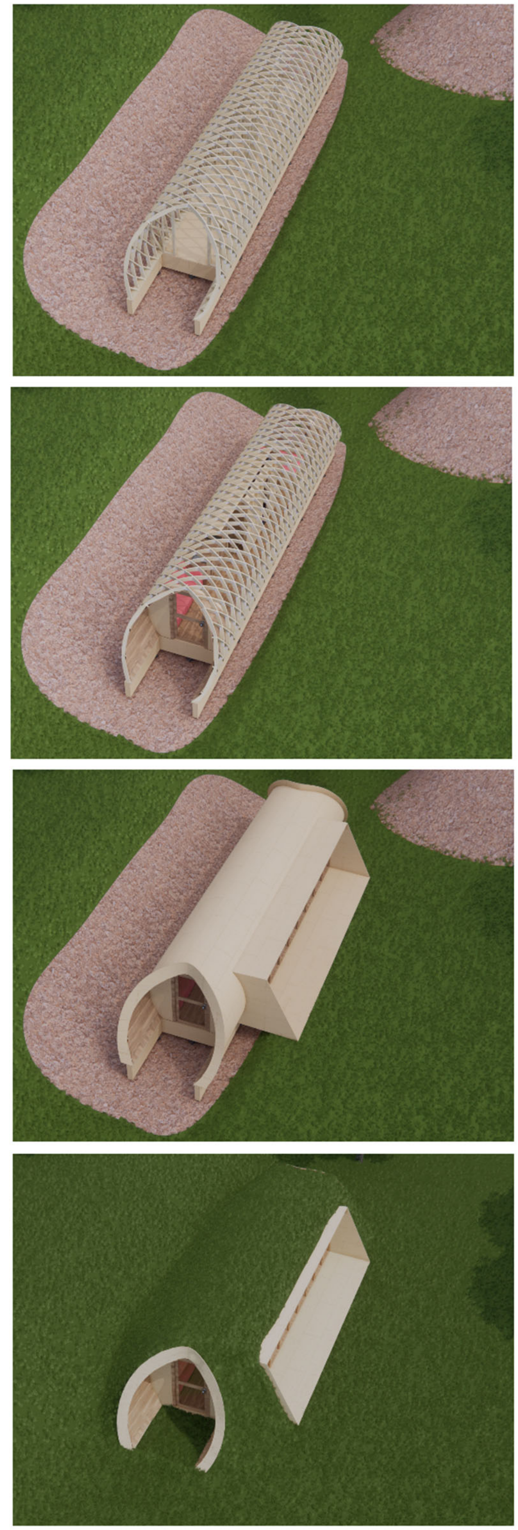




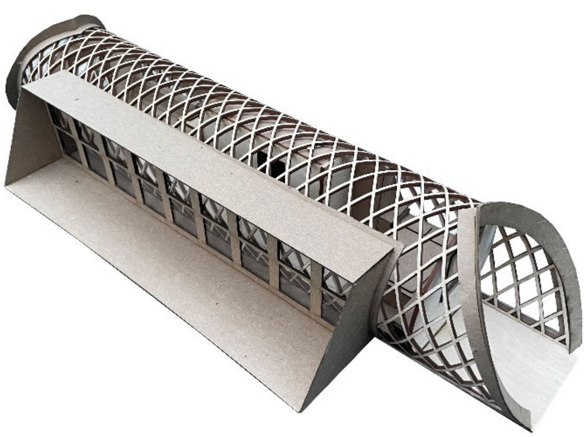


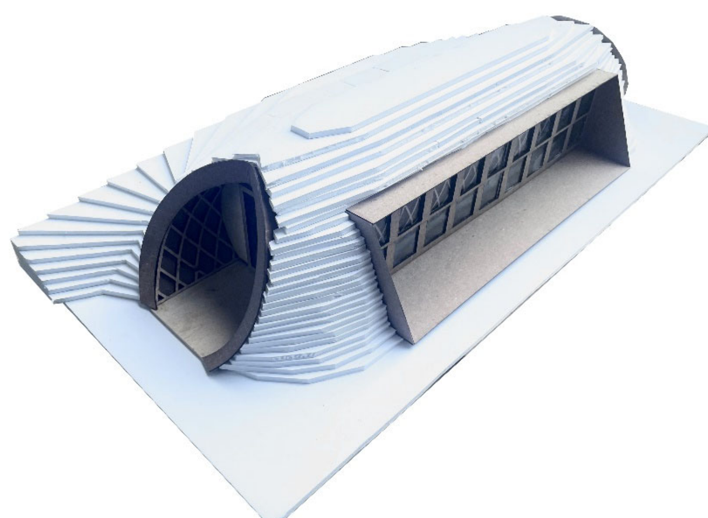
CHAPTER 9: CONCLUSIONS

The reaction of the market to high housing prices is to fulfill demand as soon as possible with what is considered to be least risky and by providing what is considered most quick to sell. This is what land developers refer to as "product." They are willing to build large houses spread over huge tracts of land because that is what is most profitable. Homebuyers ultimately pay the price for this greedy development with shoddy, placeless houses that come with enormous mortgages. The solution is to experiment in new, region specific housing. Land development as a business is sadly unconducive to this sort of experimentation.



As housing takes up so much space in the landscape, it is the most important building type to get right. Current homes are too large and too expensive to be environmentally or socially ethical. Affordable homes need to be at least tried, so that they can be proven. This subterranean prototype house is not a proposal to be built by a developer, but by individuals in a community working together. That inherently makes it more affordable to those who do not have material wealth, but wealth in ambition. This project deserves the effort that can't be supplied by one student in a single semester, but the writing of these words does not mean that I will stop working. Even now, many people who are close to me, including my own older sister, have expressed their disappointment in being unable to afford a home, even in a two income household making very normal wages. Something has to change, socially and economically, and the solution lies in how we build things.





BIBLIOGRAPHY

Archello. “Bach with Two Roofs.” Accessed November 26th, 2022.

Freear, Andrew, Elena Barthel, and Andrea Dean Oppenheimer. *Rural Studio at Twenty: Designing and Building in Hale County, Alabama.* New York: Princeton Architectural Press, 2014.

Guide to Iceland. “The Historic Glaumbær Turf Houses of North Iceland.” Accessed November 25th, 2022.

Nebraska Studies. “Living in a Sod House.” Accessed November 25th, 2022.

Prinz, Rachel Preston. *Hacking the Earthship: in Search of an Earth-Shelter that Works for Everybody*. Albuquerque: Archinia Press, 2015.

Reynolds, Michael. *Earthship Volume I: How to Build your Own.* Taos: Solar Survival Architecture, 1990.

Robert, Whitehead. *Structures by Design: Thinking, Making, Breaking*. Routledge, 2020.

Smith, Jeremy. "Soft Architecture: Is Being Finished, Finished?" Lecture Presented in Schollmier Hall, 205. February 11th, 2019.

Thorncrown Chapel. “About us.” Accessed November 25th, 2022

Weller, Chris and Erin McDowell, “Inside Coober Pedy, the Australian mining town where residents live, shop, and worship underground,” *Business Insider*, May 3rd, 2020.

Wind Rose Climatology Center “Fayetteville.” Accessed November 26th, 2022.