Exploring a High-Tech Approach to Subterranean Dwelling Environments for Commercial Implementation

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by
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Graded by: ______________ Date of Submission ______________________
Checked by: _____________ Approved by: ___________________________
ABSTRACT

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Matthew Richard Gordon

People are always looking to experience something interesting and unique when on vacation. What could be more unique than staying in a hotel that is completely underground? While people have always been amazed at natural caves and other subterranean structures, the idea of spending the night in one of these is a somewhat untried area, although it could be quite the selling point. This being the case, the idea of a subterranean hotel is not so farfetched, however there are a number of issues that arise with this project. These issues include construction and selecting the proper site and building materials to ensure strength, issues of humidity and lighting, as well as simply getting people to make this a destination on their vacation. This paper addresses these issues and discusses composition of materials and the use of a steel and concrete mixture to ensure strength and rigidity. Lighting issues are also solved using reflectively coated light tubes to gather sunlight and heat from the outside. The biggest internal issue of humidity is solved through the use of energy recovery ventilation. Finally, the cost of the hotel and the cost of operation are justified in the final section. With the ideas presented in this paper, forward thinking hoteliers could see how a property of this nature could indeed be possible and profitable.
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I. Introduction and Problem Statement

The idea of a completely “green” house (where everything is built in to nature) is something engineers and environmentalists have been striving to create for quite some time. A property that uses nature for its structure and insulation would drastically cut down on energy and maintenance costs, for example. Apart from this, a property of said nature would be very unique and quite aesthetically pleasing, and would thus draw much attention, not only from everyday persons, but also from investors and contractors looking to get in on the subterranean trend.

Currently, there are millions of hotels in the world. Only a handful of these are unique (i.e. not a typical chain hotel commercial building) with their jaw-dropping designs, scenic locations, or just plain “different-ness.” These attention-grabbing structures are often listed as some of the most successful hotels in the world, thus making them a popular destination for travelers. With this in mind, and with my recent likening to the television show “Hotel Impossible” on Travel Channel, I decided to involve this hotel idea in my senior project. Building a hotel in a cave or underground has been a new idea with some great potential, but does have its drawbacks and difficulties, such as issues of humidity and material failure, as well as getting proper sunlight. My senior project will focus on addressing these and other difficulties. This is a proper and appropriate senior project for an Industrial Engineer because it deals with sustainability, facilities planning, human factors, and the economics of engineering.

II. Background and Literature Review

Since the dawn of time, inhabitants of this earth have sought shelter in Mother Earth’s natural features such as caves, berms, hills, mountains, and the like. While not the most luxurious accommodations, these natural features provided shelter and protection from the
elements, as well as a place to call home. For these and a variety of other reasons, people have lived in such structures for thousands of years in widely spread locations around the world – generally without knowledge of the existence of similar shelters elsewhere (Bowen, 1981). Over these thousands of years, subterranean living has grown substantially in popularity and become a socially acceptable practice. History has shown us that there are three main reasons for this idea.

The first and most obvious reason was that the shell was already there (Wade, 1983). The commonly referred to “caveman” would find these naturally created locations and simply move into them. Another reason for this practice of building underground was for military purposes. France’s Maginot Line and Hitler’s underground airport are some examples of how whole mountains and grounds have been tunneled out in the name of defense. Despite these, the most common reason for subterranean living was to escape the extremes of the outside world, be it temperature, noise, creatures, or the like. One of the earliest examples of this came around 300 AD, when the Pueblo Indians in the southwestern United States went to the Cliffside region of Arizona and New Mexico and constructed stone and clay chambers referred to as “kivas” (Martindale, 1981). The stone and clay that comprised these structures provided warmth for the winter and coolness for the summer. In the north, early Eskimos created igloos and utilized a U-shaped tunnel as the entrance so as to trap the cold air outside (Klodt, 1985). Commonly believed to be the largest (and still occupied) underground living area in the world, China’s northern provinces provide housing for around ten million individuals looking to escape the harsh cold (Rudofsky, 1964).

With the continual evolution and advancement of building techniques, and the discovery of new building materials, subterranean housing has evolved and grown much since its early days. In the past decades, the number of these underground houses being constructed has
drastically increased. While the reasons for this remain mostly the same – security and comfort – a new shift towards “going green” has led many people to consider Mother Earth a precious and limited entity who’s natural resources should be utilized. With the development of modern technology and materials such as “high-performance concrete, wood treated to last indefinitely underground, low-cost permanent waterproofing systems, and computers to help with the design and performance analysis, no longer does building underground make sense only in the desert or on the side of a steep hill” (Wade, 1983). These earth-sheltered homes can be constructed almost anywhere and for a reasonable price, and are very comparable to surface dwellings. With the relatively low cost of construction and maintenance, and the new found respect people have for the environment and the preservation of Mother Earth and her limited resources, many forward-thinking hoteliers are looking to get in on this subterranean trend. Currently in development is a 100-meter deep hotel to be built in an abandoned quarry in Shanghai’s Tianma Mountain (Zhang, 2012). The idea of building a hotel completely underground or in the side of a mountain would present its own unique challenges, from earth removal and construction to humidity issues to lighting issues and many more which will be discussed and described in the following sections.

Commercial buildings of the future must be cost-effective, environmentally protective, and energy efficient, as our future earth will be faced with recued amounts of energy, water, food, and housing (Klodt, 1985). Restrictive zoning regulations prohibit building on farmland and require minimum amounts of insulation and other architectural features. For buildings in which the public will inhabit, further rules and restrictions apply, such as temperature, humidity, and vibration regulations. In developing a design for a new age subterranean or earth-built hotel, many other requirements and needs would have to be met in order for a plan to be approved and
for construction to commence. Experts in the field of subterranean contracting, consulting, and construction would provide vast invaluable knowledge and input. With the hotel being all or part underground, new modern technologies will have to be researched and sought out and made available so as to satisfy building codes and to later ensure the customer will always enjoy their stay. Key factors and issues to consider such as site location, lighting, comfortableness, and air circulation (to name a few) will be addressed in the following section.

There are many factors to consider when coming up with a design and layout for a subterranean or intra-mountain dwelling or hotel. The obvious first challenge is finding a site or location suitable for such a building. “Ideally, the house [or hotel] should be designed to fit the site rather than molding and shaping the site to fit the structure” (Klodt, 1985, p. 16). Key factors to consider when deciding upon a site location include boundaries and zoning, lot size, ground water level and annual rainfall, presence of bedrock, overall topography, sunlight, wind, vegetation, soil and subsurface conditions, and the surrounding neighborhood and community. This information can often be obtained from local realtors, soil testing firms, county engineers, and other government authorities. The specifics of the aforementioned conditions will be discussed in the proceeding report, as they can basically determine if the site is even a possibility.

Once an appropriate site is selected, the materials to be used for the construction of the establishment should be decided upon. While concrete is the most obvious choice, with its seemingly limitless forms and unmatched strength, it is not without shortcomings. Concrete is heavy and will have trouble curing in a moist, underground environment. Without using additives and strict quality control, concrete would not be a wise choice. While wood is the most commonly used material in building homes, it also falls victim to the moist subterranean
environment. Steel is often the chosen building material for these structures, as it is 2500 times as strong as concrete in tension and 50 times as strong in compression (American Institute of Steel Construction, 1980). While steel is extremely strong and readily available, it is also limited by its cost and susceptibility to corrosion. Clearly the best composition would have to be a mixture of different materials. Similarly, loading capacities for walls, roofs, and other features need to be considered when determining the type of materials to be used for construction. Other basic structural elements will be discussed in further detail in the proceeding report.

A large concern with a building or hotel of this nature is the energy performance of the property. As one of the main reasons for building underground or in a mountain is to reduce energy costs and consumption, it is often seen as the key indicator as to whether the project was a success or not. In a study on earth-sheltered dwellings in Oklahoma, which can be seen as a promising guide for other earth-sheltered properties, almost all occupants reported substantially lower energy consumption that their previous conventional property (Grondzik, 1980). An in-depth energy and economic analysis for the proposed hotel can be found in the associated section of the report.

While all these factors are indeed important and should be considered, the most important factor, in any hotelier’s opinion is the overall comfort of the consumer. If the customer is happy, they will likely return and tell others of their satisfaction with their stay. Many elements of the architectural environment influence the overall comfort, as well as the thermal characteristics, of an occupied space. See Table 1 below for a systematic depiction of said elements, of which many will be key areas of focus when planning the design and layout and contents of the subterranean hotel.
With things headed in the direction that they have been recently (shift to eco-friendly and going green, preservation of resources, advancement of building technologies, etc.) there has never been a better time to live in subterranean conditions. Although it may seem farfetched to some, an underground dwelling is very comparable to its aboveground equivalent, with solutions and fixes to any concern that consumers could have. With the success of single-family subterranean residences, it only makes sense to commercialize the idea and build a hotel of the sort. In the proceeding report, this idea is laid out in great detail and justified and concluded with an economic analysis.

<table>
<thead>
<tr>
<th>COMFORT AREA</th>
<th>CRITERION</th>
<th>INDEX</th>
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<tbody>
<tr>
<td>Thermal</td>
<td>air temperature, mean radiant temperature, relative humidity, air circulation (movement), percentage of glass; floor area, single vs. double glass, nighttime insulation measures, occupant (age, clothing, activity level)</td>
<td>thermal stress, discomfort index, bioclimatic clart, equivalent uniform temp.</td>
</tr>
<tr>
<td>Lighting</td>
<td>illumination levels for tasks, brightness ratio, percentage of glass; floor area, overhang; shading, ground surfacing, room reflectances, number of lighting directions, occupant (age)</td>
<td>direct glare, daylight factors, distribution</td>
</tr>
<tr>
<td>Spatial</td>
<td>floor area per person, field of view angles, occupant (activities, stay-time), percentage of openings in envelope</td>
<td>degree of enclosure, separation distances, plan design index</td>
</tr>
<tr>
<td>Acoustic</td>
<td>noise criteria (NC) indoors, outside noise level, direction, ground surface treatment, exterior walls, berms, courts, single vs. double glass, percentage of glass; separation distance, interior noise sources</td>
<td>intrafamily privacy, environmental noise reduction</td>
</tr>
</tbody>
</table>

*Table 1 - Criteria and Design Indices for the Architectural Environment [Boyer, 1981]*
III. Theory/Design/Methods

A) Site Selection

Before delving into discussion regarding site selection, it is important to first understand who might be interested in funding and/or undertaking this very unique venture. Ideally, the subterranean hotel would have the best chance of success if a major hotel chain, such as Marriott, were its primary owner/operator. The Marriott family of hotels is currently undergoing rapid expansion both nationally and internationally, with an opening of roughly 30,000 rooms and development of 110,000 more in the year 2012 (Leitner, 2012). Within their family of brands, the JW Marriott Hotels collection would make a fitting home for the subterranean property. The JW series offers travelers with beautiful properties in gateway cities and distinctive resort locations around the world. Marriott expects the JW portfolio to encompass 80 properties in 29 countries (57 properties at end of 2012). With the dominating presence that Marriott has in the hotel industry, and with their expertise in marketing and promoting their new properties under their various brands, the subterranean hotel would be destined for success if taken on by JW Marriott Hotels. As it is a very unique opportunity, Marriott would almost certainly be interested in undertaking a large and obscure project such as this.

The first step, now that a target company has been chosen, is to find an attractive potential site for the hotel to be constructed. The goal in selecting a site is to find one whose natural landscape could be incorporated into the design of the hotel, say in a cave for example. This is vital because uniqueness and naturalness, not commercialized or standard, are being sought out in the design of this hotel. Also, the natural landscape aids in the structural stability and support of the building, as well as in keeping with a “green” ideology. This “natural-design” idea also makes the hotel less susceptible to fire, high winds, hailstorms, and tornadoes.
Earthquakes, however, is something that should definitely be taken into account when picking the building site. Since the structure would be completely in the earth, an earthquake could have devastating effects and crumble the property, so the hotel should be situated away from known fault lines or active earthquake zones. Obviously the site should be near local attractions and in an area where tourists often travel, so as hotel guests have activities to do when not in their room or exploring the stunning property. Taking these into account, a large cave near a large body of water would be an ideal building site for the subterranean resort.

**B) Construction/Facility Plan**

While we are trying to find a cave-like structure and keep as much natural cave walls and features as possible, the surrounding land and material will ultimately have to be dug up, demolished, and/or removed in order to accommodate the hotel’s building plans. The main entrance, however, will likely not require much material removal since it is planned to be the only aboveground structure on the property. The entrance will be constructed with the most luxurious columns and stones, with an entirely front glass wall so as to let in as much light as possible. Since this main lobby will be the first thing guests see when they approach the property, it makes perfect sense to have it stand out and make a statement. This ornate room is where guests will check in, drop off their car key to the valet, and receive information regarding the hotel. The main lobby will have three hallways, all leading to different places. The main hallway will lead to several elevators, all of which go down to one of the two floors of guest rooms, which are completely underground. The second hallway leads to the shipping, receiving, loading, and storage area. The last hallway leads to a set of stairs that allow access to some of the hotel’s amenities, such as a completely underground gourmet restaurant and cafeteria, which
will be discussed shortly. But let’s go back to the construction of the underground rooms and hallways first.

As mentioned above, much of the land and surfaces where our underground rooms and hallways will be constructed will have to be removed, however it is first wise to take into account the strength and composition of the materials in the land before doing so. “Strength properties of soils are important for the design of footings, retaining walls, and for finished slopes, excavation, and stability of natural slopes around the structure” (Klodt, 1985, p. 40). The composition of the material in the walls and floors that we are planning to demolish and construct upon must take into account the specifications in the tables on the next page (Tables 2-4). If, after studying the compositions of the land, walls, and features down in our cave, it is deemed safe, then demolition will begin. Two long main hallways (one on each floor) will serve as access to guest rooms. The material will have to be removed and/or shaped so as to afford the placement of arches composed of steel beams (coated in an anti-rust material) and concrete slabs. These arches will serve as the main support for the walls and door frames, and the ceiling of the hallways so that there will be no risk of a collapse. For the sake of long-lasting rigidity, and more simply peace-of-mind, this concrete and steel support structure (and the construction of the hotel in general) would need to satisfy local building codes or an opening day would not be possible.

While there is much more that could be discussed regarding the materials and processes used for the construction of this hotel, it is quite out of the scope of the project and therefore I will not be discussing it in this paper. However, there are a few key features of the hotel that should be discussed as they deal with much of the facilities planning aspect of Industrial Engineering.
<table>
<thead>
<tr>
<th>Major Divisions</th>
<th>Group Symbols</th>
<th>Typical Names</th>
</tr>
</thead>
<tbody>
<tr>
<td>COARSE-CRAGNED SOILS</td>
<td>GW</td>
<td>Well-graded gravels and gravel-sand mixtures, little or no fines</td>
</tr>
<tr>
<td>SANDS</td>
<td>GP</td>
<td>Poorly graded gravels and gravel-sand mixtures, little or no fines</td>
</tr>
<tr>
<td>SANDS WITH FINES</td>
<td>GM</td>
<td>Silty gravels, gravel-sand-silt mixtures</td>
</tr>
<tr>
<td>CLEAN SANDS</td>
<td>GC</td>
<td>Clayey gravels, gravel-sand-clay mixtures</td>
</tr>
<tr>
<td>SANDS WITH FINES</td>
<td>SW</td>
<td>Well-graded sands and gravelly sands, little or no fines</td>
</tr>
<tr>
<td>CLEAN SANDS</td>
<td>SP</td>
<td>Poorly graded sands and gravelly sands, little or no fines</td>
</tr>
<tr>
<td>SANDS WITH FINES</td>
<td>SM</td>
<td>Silty sands, sand-silt mixtures</td>
</tr>
<tr>
<td>FINER-CRAGNED SOILS</td>
<td>SC</td>
<td>Clayey sands, sand-clay mixtures</td>
</tr>
<tr>
<td>SILTS AND CLAYS</td>
<td>ML</td>
<td>Inorganic silts, very fine sands, rock flour, silty or clayey fine sands</td>
</tr>
<tr>
<td>SILTS AND CLAYS</td>
<td>CL</td>
<td>Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays</td>
</tr>
<tr>
<td>SILTS AND CLAYS</td>
<td>OL</td>
<td>Organic silts and organic silty clays of low plasticity</td>
</tr>
<tr>
<td>SILTS AND CLAYS</td>
<td>MH</td>
<td>Inorganic silts, micaceous or diatomaceous fine sands or silts, elastic silts</td>
</tr>
<tr>
<td>SILTS AND CLAYS</td>
<td>CH</td>
<td>Inorganic clays of high plasticity, fat clays</td>
</tr>
<tr>
<td>SILTS AND CLAYS</td>
<td>OH</td>
<td>Organic clays of medium to high plasticity</td>
</tr>
<tr>
<td>Highly Organic Soils</td>
<td>PT</td>
<td>Peat, muck and other highly organic soils</td>
</tr>
</tbody>
</table>

*Based on the material passing the 3-in. (75-mm) sieve.

Table 2 - Unified Soil Classification Chart [ASTM D 2487]
Table 3 - Presumptive Bearing Values Allowed by the Uniform Building Code in the Absence of a Soils Investigation

<table>
<thead>
<tr>
<th>Class of Materials</th>
<th>Allowable Foundation Pressure Lbs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Massive Crystalline Bedrock</td>
<td>4000</td>
</tr>
<tr>
<td>2. Sedimentary and Foliated Rock</td>
<td>2000</td>
</tr>
<tr>
<td>3. Sandy Gravel and/or Gravel (GW and GP)</td>
<td>2000</td>
</tr>
<tr>
<td>4. Sand, Silty Sand, Clayey Sand, Silty Gravel and Clayey Gravel (SW, SP, SM, SC, GM and GC)</td>
<td>1500</td>
</tr>
<tr>
<td>5. Clay, Sandy Clay, Silty Clay and Clayey Silt (CL, ML, MH and CH)</td>
<td>1000</td>
</tr>
</tbody>
</table>

1For soil classifications OL, OH and PT (i.e., organic clays and peat), a foundation investigation shall be required.

2All values of allowable foundation pressure are for footings having a minimum width of 12 inches and a minimum depth of 12 inches into natural grade. Except as in Footnote 3 below, increase of 20 percent allowed for each additional foot of width and/or depth to a maximum value of three times the designated value.

3No increase for width is allowed.

While the uniqueness of spending the night underground in a cave is quite appealing, possessing other great amenities would be key to the continual success of this hotel. One such amenity I will discuss is developing a five star gourmet restaurant, which would feature top chefs from around the world. Adjacent to the restaurant would be a cafeteria for employees to eat

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and/or lounge. As underground space is limited, and with the huge costs associated with demolishing parts of the cave to make more, the restaurant and cafeteria area should be designed only with the bare square footage requirements needed to meet certifications. For a dinner service, which would be the largest service of the day, the restaurant will have to give a maximum capacity number and allowances of least square footage requirements will have to be calculated (Tompkins, White, Bozer, & Tanchoco, 2010). Likewise, based on how many meals will be served in a typical full day, there is a minimum amount of area required for the kitchen, as evidenced in the table below:

<table>
<thead>
<tr>
<th>Number of Meals Served</th>
<th>Area Requirements (ft²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100-200</td>
<td>500-1000</td>
</tr>
<tr>
<td>200-400</td>
<td>800-1600</td>
</tr>
<tr>
<td>400-800</td>
<td>1400-2800</td>
</tr>
<tr>
<td>800-1300</td>
<td>2400-3900</td>
</tr>
<tr>
<td>1300-2000</td>
<td>3250-5000</td>
</tr>
<tr>
<td>2000-3000</td>
<td>4000-6000</td>
</tr>
<tr>
<td>3000-5000</td>
<td>5500-9250</td>
</tr>
</tbody>
</table>

Table 5 - Space Requirements for Full Kitchens [Kotschevar, L.H., and Terrall, 1977]

Another key thing to consider is the restrooms for the customers of the restaurant and the hotel/lobby in general. While there are generally adopted standards for amounts of restrooms given number of people (Tompkins et al., 2010, p. 147), this is only a base for our underground hotel, as drainage and septic tanks would likely pose issues which above-ground properties do not face.

While thinking about the space required for the bathrooms and the exact minimum square footage required for the restaurant might seem a little farfetched, it is actually quite important in this situation, primarily due to the fact that it is very expensive to remove naturally formed caves
and rock formations, because of the risk of collapse if not done properly. Also from an economic and environmental standpoint, one should only remove as much material as absolutely necessary. Keeping the beauty of the natural formations of the cave would give the restaurant an ambiance unlike any other. While the design and construction of this subterranean hotel is unique and different, and could be discussed in far greater detail, the focus of this senior project is on solving the problem of living underground. Problems such as obtaining natural sunlight, ridding humidity, and fighting off that feeling of claustrophobia, will all be discussed in the immediate following section.

C) Issues with Subterranean Hotel and Their Solutions

Without a doubt, the most key problem with a subterranean residence or hotel is the fact that it’s underground and thus will experience the effects of such conditions. These conditions include moisture issues, humidity, and darkness (lack of natural light). In this section I attempt to address these issues.

The first issue faced with underground dwellings is dealing with the moisture of the earth and the cave in which the property is built in or upon. Due to the fact that the earth is more humid than the surrounding air, this problem needs to be addressed or else issues such as mold and property damage can arise when it is least expected. *Stachybotrys chartarum* is a greenish-blackish mold that grows when there is moisture from water damage, excess humidity, water leaks, condensation, water infiltration, or flooding (http://www.cdc.gov/mold/stachy.htm). *Cladosporium* is another fungi that grow in pipelines and ventilation systems, as they are abundant in the outdoor air. Mold can be dangerous if left untreated, and can lead to those who come into contact with it or breathe it in contracting fever, shortness of breath, or even fungal
infection of the lungs.

The easiest way to deal with this problem is to prevent any moisture from building up and causing water damage in the first place, i.e. preventative maintenance. First, the hotel should be properly sealed at all areas of jointure, to ensure no liquid can seep through the cracks. “A low-water/rich-cement mixes and waterstops at all cold joints will provide a shell that is intrinsically waterproof. The second line of defense is the waterproofing materials placed over the outside of the shell” (Wade, 1983, p. 156). There are numerous types of waterproofing materials, but for our case the most ideal would be a performed membrane/roll goods type of material. It is dubbed the name ‘roll goods’ due to the fact that it is purchased in large rolls and made of several materials bonded together, thereby offsetting the disadvantages of each. It is advantageous over the other types because it is fully adherent, so water cannot travel behind membrane. The W.R. Grace Bituthene system (Figure 1) is a specific example of what this type of waterproofing would look like.
Another thing to prevent issues of water damage is to prevent water from even reaching the building, which can best be done with an effective drainage system. “By arranging land contours, drainage tiles, and the content of backfill surrounding the underground hotel, water can effectively be kept from contact” (Wade, 1983, p. 153). In the rainy season, moving water needs to be diverted away from the property using drainage channels and grading of the land surrounding the property. Below the surface, drainage channels should take any water (that has been left to seep through) and pump it away from the main cave or structure area of our hotel and at least 100 feet away to where it can drain into open air (Wade, 1983). While one may think a cave will have dripping water issues, these issues can be solved with the implementation of the aforementioned strategies.

Similar to the moisture problems, another key area which would have to be dealt with – not only for safety but for the overall customer experience – is with the humidity inside the guest rooms and the property in general. Apart from the main lobby, the entire hotel will suffer from the lack of any sort of naturally flowing air, and thus it will be hot, stuffy, humid, and overall just unpleasant inside. This lack of ventilation can lead to one being exposed to excess carbon dioxide and suffer from a lack of oxygen. The use of an energy-recovery ventilator, also known as an ERV, or a heat-recovery ventilator, also known as an HRV, is of vital importance in underground homes. These systems work by the process of exchanging the energy contained in normally exhausted building air and using it to treat or precondition the incoming outdoor ventilation air ("Energy Recovery Ventilation," Wikipedia: The Free Encyclopedia). Basically, during the cooling season, this ERV system works to cool and dehumidify the incoming, outside air by taking the rejected heat and sending it into the exhaust airstream. During the heating
season, the system works in reverse and the system draws heat from the exhaust airstream in order to pre-heat the incoming air.

Apart from lowering humidity, these systems can also remove odors and harmful airborne toxins, as well as dilute pollutants from the building. While not cheap to install, especially for a commercial application such as the one here, they do offer a reasonable cost of operation, and are the best solution for humidity issues with underground dwellings. An ERV system also satisfies the ASHRAE ventilation & energy standards.

The utilization of energy recovery ventilation will allow for healthy, breathable air, which will be completely free of toxins and/or bacteria.

Finally, the most visible problem with building the majority of a property underground is the lack of natural sunlight, or any light in general. As mentioned before, the entrance to the hotel will be above-ground and with numerous glass windows and lots of natural sunlight. This
is quite far from the case once guests enter the two guest floors, which are completely underground and not connected directly to the outside. This being the case, getting any sort of natural light in to the rooms or hallways would require some creativity. One idea would be to implement skylights to each of the rooms on the top level of guest floors. These skylights would have to be double or triple-paned and sealed so as to not allow any moisture or anything in. The skylights would each have to have a channel above them so as to let sunlight in. This could be dangerous and expensive, and thus would not be an ideal option. After some research, the best option turns out to be a series/collection of reflective tubing leading from the surface and going into all the areas where light is requested. Spectralight Infinity Tubing by Solatube (Figure 3) has the most reflective surface in the world, and it transfers maximum daylight with minimum absorption losses, even when going to hard-to-reach places. This would be the most efficient way to light up the rooms and hallways in the hotel, and tubes can be connected and split so that the lower level areas can be reached as well. These tubes will have flaps, which will close off the end and black out the tube if the guest wishes to not have sunlight. During times when natural light is unavailable such as evenings and stormy days, rooms and hallways will of course be equipped with both recessed and track lighting, which will provide adequate illumination without being too harsh. Adding unique lighting fixtures and artwork to the rooms, along with their unique cave-like interior will cause guests to not think about the fact that they are in an underground cavern but instead think about how wonderful of an experience they are having in a location they didn’t even know existed before
coming to it. This will also help to relieve the feeling of claustrophobia, which many guests would likely experience due to the confining nature of the rooms and the hotel in general.

Another issue, which would need to be addressed when planning for the underground dwelling, is how to properly and efficiently cool and heat the property. No matter what time of year it is, the temperature of the soil surrounding the property will not drop below 50º Fahrenheit. The interior temperature conditions are “naturally” comfortable and easy to control as well. Using a system of passive annual heat storage, the heat is captured and stored in the dwelling’s “thermal mass.” The thermal mass continuously radiates its warmth to the interior while the earth surrounding the underground structure adds to the process as it buffers the cold winds and moderates the extreme heat or cold of the exterior. During hot weather, the underground hotel will stay cool relative to its climatic conditions (Klodt, 1985). However, as a heating and cooling system is almost required for comfortable living these days, many owners and operators of subterranean properties have turned to a system of solar heating.

While solar panels are often a common choice with solar heating, they are an active system and thus require an expensive installation and pricey maintenance, as well as decreased efficiency over time. A more widely used method in the area of underground buildings is known as passive solar heating. The most optimal, popular, and simplest method of passive solar heating is known as the direct gain method. In direct gain, “the sun simply penetrates through the fixed or operable south-facing windows of the habitable space and strikes a thermal storage wall or floor” (Klodt 1985, p. 188). In our case, the sun will penetrate through the reflectively-coated tunnels we have installed, allowing the natural sunlight to collect and gather along said wall or floor. Because of the dense storage media’s thermal properties, color, and mass, the absorbed and stored heat slowly releases when the air temperature drops below the temperature
of the mass.

As far as cooling the interior of the subterranean hotel, a system known as passive cooling will be utilized so as to keep the temperature comfortable for guests during the hot summer season. “The primary means of passive cooling with an earth shelter is actual contact with the earth” (Klodt, 1985, p. 203). These shelters, being built either fully or partially into the earth, reduce exposure to outside temperatures as well as benefitting from the earth’s cool mass by conduction. “Earth shelters built of dense materials such as concrete [as is the case with our subterranean hotel] have the thermal mass of the structure as an advantage for storing coolness from the winter” (Klodt, 1985, p. 203). Passive solar cooling uses cool surfaces and the natural flow of thermal energy to create air movement; when the proper amount of this air movement is combined with the correct relative humidity, comfortable interior conditions are relatively easily created.
IV. Financial Analysis

Apart from being unique and different, and apart from the ideal human factors/conditions that we can achieve with some modern technologies, this subterranean hotel (and any underground dwelling) will be surprisingly reasonable in price to construct and operate. The following passages will attempt to explain this phenomena.

To begin, the cost of constructing one of these behemoths is not as high as one might think. It is much cheaper to remove earth than it is to build on top of it. In general, “Construction costs for existing earth shelters range from 25 percent less to 10 percent more than equivalent conventional structures” (Klodt, 1985, p. 265). However, earth sheltered properties (like our subterranean hotel) can be built in the lower price range by studying and avoiding key pitfalls such as poor site selection, poor quality control and improper concrete and steel placement. These materials we will be using – concrete and steel – will help to conserve our valuable forests and last longer than any other material out there. Since the features of the cave will help to form the walls of many of the guest rooms, we will be saving much on construction costs in that sense as well. There is also value found in the safety of building underground, as hail, high winds or tornadoes will not appreciably damage an underground dwelling. “Even in an earthquake, the ground around the [property] will vibrate less as it goes deeper, and the concrete foundations of these [properties] are considered to be earthquake-resistant. In addition, the exterior[s] of these [underground dwellings] are made with metal studs and concrete, which makes them fire-resistant” (See Underground homes in Bibliography). These natural properties/advantages have allowed insurers to give much better rates to insure structures built underground, as they understand the risks of something going horribly wrong when Mother Nature strikes is significantly lower. Also, because of their lower cost to build, properties like
this are generally appraised at a lower price and thus property taxes will be lower.

Annual maintenance costs of our underground hotel will also be considerably lower than the above-ground counterpart considering there are no (or limited) windows to wash, no (or limited) exterior to paint or clean, no roof or gutters to repair and empty out, and limited need of security personnel. Obviously, a maintenance staff will still be utilized for the interior of the building, and to maintain the aesthetically pleasing standards management has set.

Most of the savings, however, will come from the reduced use of energy to heat and cool the property, as discussed in the previous section. When looking at a cost breakdown of the electricity a hotel uses, one can immediately see how large of a consumption HVAC is (Figure 5) and how much less energy will be used in our subterranean hotel due to the alternative methods of heating and cooling which will be implemented in our design.

![Figure 5 - Typical Electricity Consumption for U.S. Hotel](source)

With the implementation of a passive solar heating and cooling system, the need for a conventional air conditioning and heating system is virtually eliminated, which can add up to significant annual energy savings. When you combine this, along with the decreased need for maintenance and the lowered construction costs, its easy to see why building underground is the
hot new trend, and what better way to make a big statement that to construct an entire hotel underground?

**A) Cost Breakdown/Estimation**

Due to the fact that subterranean properties of a commercial nature and purpose are rather scarce, information on their overall construction cost is difficult to dig up. While some costs may be calculated (such as appliances and fixtures), other costs are more difficult to estimate (such as energy consumption and material cost and rent). Below you will find a generic cost estimation for the construction of the subterranean hotel.

The first cost to determine is the price to remove earth. Homewyse, a website for “smart home decisions” has given the following information regarding earth removal for the Los Angeles area.

![Cost to Remove Dirt](www.homewyse.com/services/cost_to_remove_dirt.html)

*Figure 6 - Cost to Remove Dirt [www.homewyse.com/services/cost_to_remove_dirt.html]*
For the general construction of a hotel, the cost to construct (per sq. foot) is largely based on location. RSMeans, the industry leader in construction cost estimating and analysis, developed a graph showing the variation in cost (Figure 7). Given the construction base price/estimate for a hotel in Los Angeles, California (as this was the zip code used for the earth removal estimate), one is able to make an estimate for the cost to construct an underground dwelling. In this case, given its commercial and subterranean nature, a value of $210/ft² would be a fair estimate.

As for the interior of the hotel, the costs would be more or less the same as that of the aboveground counterpart. JN+A & HVS Design produces an annual guide for hotel cost estimating, broken down into a number of detailed items and categorized by the class/tier of the hotel. Below is just an excerpt that shows the great detail the guide goes into when estimating costs of items that are assumed to be included (based on the tier of the hotel) per guestroom (Figure 8). For a full, detailed cost breakdown, and definitions of the different tiers and categories, one should reference the guide, which is publicly available on their website (See Nehmer & Feldman, 2012).
Obviously, for our subterranean hotel, numerous other costs (apart from those mentioned in the guide) will have to be included in the estimation, such as the cost for the light tubing system and the energy recovery ventilation systems. For the former, the base kit, which includes the diffuser and dome for light input, prices out around $445 per kit; the tubing costs around $438 per 10-foot section (http://www.solatubescotland.co.uk/price-guide.php). Since the rooms will be far underground, a great deal of tubing will be required, which will be quite pricey. However, it will dramatically cut energy costs and is a necessary item for guest comfort.

For an energy recovery ventilation system, the cost ranges from around $1,000 - $2,000 depending on the quality of the system (Figure 9).
With these costs in mind, one can get an idea of the overall cost of a hotel of this nature and see just how expensive it is to construct a hotel in general.

V. Conclusion

This project dealt with the key issues that arrive when planning for the construction and development of a subterranean hotel, or any subterranean property for that matter. Building problems, such as issues with common building materials and their lack of strength or structural integrity when placed in the ground, were solved with the use of a concrete and steel mixture. Issues with the layout of the facility and the amount of square footage necessary for certain features were addressed with data on minimum required space acquired from facilities planning literature. The problems with living underground such as lighting were addressed with the use of highly reflective lighting tubes. Humidity and ventilation issues were solved with the use of an energy recovery ventilator, which simply uses the stale air already inside to filter the fresh, clean air from the outside. The cost of building such a property was determined to be less than its aboveground counterpart, and the energy savings would be massive. With these key issues
addressed, all of our objectives outlined in the introduction section have been accomplished.

One of the biggest lessons learned when doing this project is that there is a great amount of planning and development that goes into creating a hotel, let alone a hotel completely underground. Given more time, my senior project could address more issues that would arise from this increased amount of planning that would be done. Unfortunately, I was only able to focus on the key issues described above.

Given the findings and solutions to said key issues, I would recommend Marriott or any other large chain hotel company look into developing a subterranean property to add to their collection. It would not only be something unique and something to set the company apart from their competition, but it would also be quite the money-making venture, and could lead to other developments in the subterranean field.
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