INQUIRY INTO THE UNDERWATER STRUCTURES: ARCHITECTURAL APPROACHES TO DESIGN CONSIDERATIONS

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ABSTRACT

INQUIRY INTO THE UNDERWATER STRUCTURES:
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Underwater has always been attractive and curiosity for human beings. Exploring, employing and being part of underwater has been a challenge for them at all times. The first underwater structures were products of engineering studies and have been used for fields of scientific researches and observations, military purposes and obtaining energy for centuries. However, underwater is a new medium for human for accommodation and entertainment purposes; and correspondingly new subject which is worth to study for architects. Designing underwater structures became a race between architects and engineers during last years. Accordingly, underwater hotel and restaurant projects were realized. Currently, underwater structures can uttered as a fantasy and a new understanding for architecture, however in the future underwater may be suggested as a new accommodation area.

The thesis aims to point out the design considerations of underwater structures from not merely engineering, but also architectural aspects. Designing underwater has its own principles and characteristics and these should be asserted under the light of the study on former structures. On the other hand, basic criteria and purposes of architectural aspects for underwater structures should be defined to meet requirements of human. To achieve that, parameters will be pointed out and interpreted according to the conditions and limitations of the environment in order to set the fundamentals for architectural approaches to underwater design. A comparative study on contemporary examples will be made to evaluate these parameters and comments will be made under the light of the evaluation.

Keywords: Underwater structures, architectural approaches to underwater design, underwater hotels, underwater restaurants, architectural design considerations.

ÖZ

SUALTI YAPILARI ÜZERİNE BİR ARAŞTIRMA:
TASARIM İLKELERİNE MİMARİ YAKLAŞIMLAR

Koyuncu, Dilşad
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Sualtı daima insanları cezbetmiş ve onlar için merak konusu olmuştur. Sualtını inceleme, kullanma ve onun bir parçası olabilme insan için her zaman bir meydan okumaya dönüşmüştür. İlk sualtı yapıları mühendislik ürünleridir ve yüzyıllarca bilimsel gözlem ve araştırma, askeri ve enerji üretimi alanlarında kullanılmıştır. Bunu karşın, sualtı barınmak ve eğlenmek için yeni bir ortam; mimarlar için ise çalışmaya değer yeni bir konudur. Son yıllarda sualtı tasarımı mimarlar ve mühendisler arasında bir yarışa dönüşmüştür. Bunun sonucunda, sualtı otel ve restoran projeleri gerçekleştirilmiştir. Şu anda, bu konu fantezi ve yeni bir mimarlık anlayışı olarak değerlendirilse de, gelecekte yeni yaşam alanı olarak sualtının ileri sürülmesi olasıdır.

Bu çalışma sualtı yapılarının tasarım ilkelerini sadece mühendislik değil, mimari açıdan da ortaya koymayı amaçlamaktadır. Sualtı tasarımının kendine has prensip ve özellikleri mevcut yapıların ışığı altında değerlendirilmelidir. Ayrıca bu yapıların, insanların gereksinimlerini karşılayabilmesi için; mimari açıdan değerlendirilmesini sağlayacak temel kriter ve kararları tanımlanmalıdır. Bunu gerçekleştirebilmek için, çevrenin koşul ve sınırlandırmalarına uygun olarak sualtı tasarımına mimari yaklaşımı belirleyecek ilkeler ortaya konulup açıklanacaktır. Belirlenen ilkeler, çağdaş örnekler üzerinden karşılaştırmalarla değerlendirilip, bu değerlendirme ışığında yorumlanacaktır.

Anahtar Kelimeler: Sualtı yapıları, sualtı tasarımına mimari yaklaşımlar, sualtı otelleri, sualtı restoranları, mimari tasarım ilkeleri.

To,

My Family

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CHAPTER 1

INTRODUCTION

Underwater has always attracted human beings and it has been a curiosity and challenge for them. People have always desired to explore the mysterious world of underwater. In addition they struggled to utilize and being part of it. Accordingly, many attempts were carried out and various techniques, vehicles and structures, for instance submarines and underwater habitats, were developed to achieve these goals. Applications concerning underwater have been carried on various fields, such as scientific researches and observations, military purposes, mining industries and obtaining energy. However, underwater is a comparatively new medium for human to use for accommodation and entertainment with its unique characteristics and providing unusual experiences. Although many proposals were achieved by architects so far, only few of them were able to be realized.

Developments in technology gave architects courage to design in new environments and search for new trends. Among them, underwater design is a new concept and it is different from the terrestrial ones which architects are familiar with. Water has been utilized with different approaches by designers for thousands of years. It has been played an important role in the developments of cities. Water has been integrated into architecture itself as a design element in many ways, for instance a surface of a building, interior design element and landscape element. On the other hand, underwater is a new subject which is worth to study for architects.

Although, underwater structures can be stated as “a fantasy and a searching for new styles in architecture” for now; in the future, design and construction of underwater structures, even underwater cities, may be a need. At the beginning of 21st century designing underwater structures became a race between architects and engineers since these structures provide differentiations especially for commercial purposes.

Additionally, up to now designers carried out projects, such as hotel and restaurants which can be declared as architectural approaches to this topic. In fact the current underwater technology is capable to propose underwater structures which will meet the space requirements and provide appropriate quality and comfort to live.

1.1 Argument

Along with curiosity, challenge and desire; developments in marine technology and attempts to propose spaces under water by architects began to be an outstanding subject especially in recent years. Therefore the study on architectural approaches to underwater design and its considerations will be valuable for architects. This thesis will focus on architectural aspects for underwater structures and particularly defining architectural design parameters.

1.2 Objectives

This study is a start point for the future research and possible applications by providing outstanding data that will be valuable. It will also contribute to the poor architectural literature on this topic. This thesis aims to point out the design considerations of underwater structures depending on not merely engineering but also the architectural aspects.

One of the main objectives of this study is defining architectural design parameters according to the conditions and limitations of the environment in order to set the fundamentals for architectural approaches to underwater design.

It should be emphasized that, design of an ideal underwater structures is a specific research matter of which each subject should be studied in detail. Therefore, the intention of this study is not to lay out the ideal underwater structure in terms of architectural manner but rather to constitute a background and define some basic criteria and objectives for architectural aspects.

1.3 Methodology

In the first stage of study former examples from engineering standpoint will be studied to constitute a background. Subsequently, architectural design parameters will be defined and explained according to the conditions and limitations of the environment in order to set the fundamentals for architectural approaches to underwater design. After defining the parameters, a comparative study on contemporary examples will be performed and each example will be studied one by one. The applicable parameters will be evaluated focusing on the examples to discuss the design considerations from architectural point of view. Results of the comparison and comments about the examples will be presented with tables and figures. In addition several alternatives and suggestions relating to examples will be offered to constitute a background for further applications and researches.

1.4 Disposition

Second chapter focuses on the significance of water and applications relating to underwater. The attempts which were carried out to utilize and being part of underwater will be discussed. Underwater city projects will be introduced as a new accommodation area which is more feasible than space settlements.

Third chapter is a review of former underwater structures to constitute a background for architects. Architecture adopts technologies of other fields in new environments. From this perspective, brief information about submarines and underwater habitats will be introduced.

In fourth chapter, adequate knowledge about conditions and limitations of the environment and basic design considerations from engineering point of view will be provided. Before designing underwater structures, such as hotels and restaurants, architects should comprehend the fundamentals of underwater design through former structures.

Finally, in fifth chapter architectural approaches to underwater design will be discussed trough contemporary examples. Environmental forces of the medium will be noted, which articulate the architecture, with an indication of their differences from terrestrial ones. Design goals will be mentioned which should be taken into consideration to achieve a livable space under water. Architectural design parameters will be defined and a comparative study on contemporary examples will be performed with reference to these parameters. Results of this comparative study will be discussed with comments and suggestions.

CHAPTER 2

SIGNIFICANCE OF WATER AND APPLICATIONS CONCERNING UNDERWATER THROUGHOUT THE HISTORY

> In our time, water as life's origin symbolizes - despite ecological catastrophes - the dream of living in a symbiotic relationship with nature, much closer than would ever be possible on dry land. The oceans have an abundance of resources, unlimited energy reserves, and a seemingly endless supply of foodstuffs. Goods can be transported along a network of waterways that have to be neither constructed nor maintained. Town planners, architects, technicians, scientists, visionaries, inventors, and individualists have started to explore the utopian realms of water as a place to live. Dwellings, settlements, and cities for hundreds of thousands of inhabitants are already on the drawing board. [1]

To date, all civilizations depended on water for development, expansion, or simple survival and achieved these by means of several ways. Firstly, rivers were occupied by settlements throughout their navigable lengths; second, inland seas were utilized as safe areas for commercial transport and colonization. Finally, the oceans were used for exploration, expansion of populations, and commerce between continents.[2] The vital need of water rise to important engineering constructions at a very early stage in history. [3] On the other hand, water played an important role in the mythology, religion and rituals of all cultures through out the history with its symbolic **meanings**. It was regarded as one of the basic elements of the universe along with earth, air and fire. Water is accepted as the symbol for life and source of

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[1] C. Burchard and F. Flesche, *Water House*, ed. F. Flesche (Munich: Prestel Verlag, 2005), 8.

[2] F. B. George, foreword to *Living and Working in the Sea,* 2nd ed., *by* J. M. Miller and I. G. Koblick (Plymouth: Five Corners Publications, Ltd., 1995) xi.

[3] H. Dreiseitl, D. Grau and K. H. C. Ludwig**,** *Waterscapes: Planning, Building and Designing with Water* (Germany: Birkhauser, 2001), 43.

life. “All life depends on water; nothing escapes its influence, and nothing lives without it”. [4]

In contrast to the “life-giving” character of water, it also has been a symbol of death and can be perceived as “empty, dark and cold”. Apart from life and death, there are other meanings attributed to water. For example, drinking special water is believed to bring good health and abundant water represents fertility. Water is a symbol of chastity when it is pure and clear because of “its power as a cleansing agent”. [5] Besides, it is crucial for human beings and “was the most fundamental building block of the universe – irreducible and indestructible – but could not explain where it ultimately came from”. [6]

As asserted by Moore and Lidz; “fountains, rivers, pools, and ocean” are the ways that architecture and water relate. Firstly, important urban places were designated by **fountains** in towns and cities all through the history. Secondly, **rivers** and **man made canals** have been used for communication, connection and linking cities and empires. [7] Canals were excavated to allow access to the inner parts of the town, as a result streets and waterways were interlocked in cities as in the case of Venice. Thirdly, designers construct artificial **pools** in the absence of lakes to hold water at rest. [8] Finally, **oceans** and **seas** are huge volumes of water that move within themselves. Besides, they can be affirmed as the beginning and end of the water cycle.[9]

As mentioned above, water has been used by architects and urban planners as a design element. Moreover, human beings have been living and working on water since prehistoric times of the history. The **floating** and **fixed habitations** are

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[4] C. W. Moore and J. Lidz, *Water+Architecture* (Japan: Thames and Hudson Ltd., 1994), 17.

[5] Ibid., 17-20.

[6] Ibid., 40.

[7] Ibid., 20-21.

[8] Ibid., 125.

[9] Ibid., 157-158.

settlements on water which are still being used today. They can be generally in three forms, such as pile dwellings, rafts and ships. Amsterdam, St. Petersburg and Venice are the cities that were completely built on piles driven into sea bed. Having thousands of years of tradition, conventional houseboats with a ship's hull are integral parts of many major cities in China, India, Thailand, Cambodia and Vietnam. The houseboats in these regions serve as dwellings, large workshops and commercial units.[10]

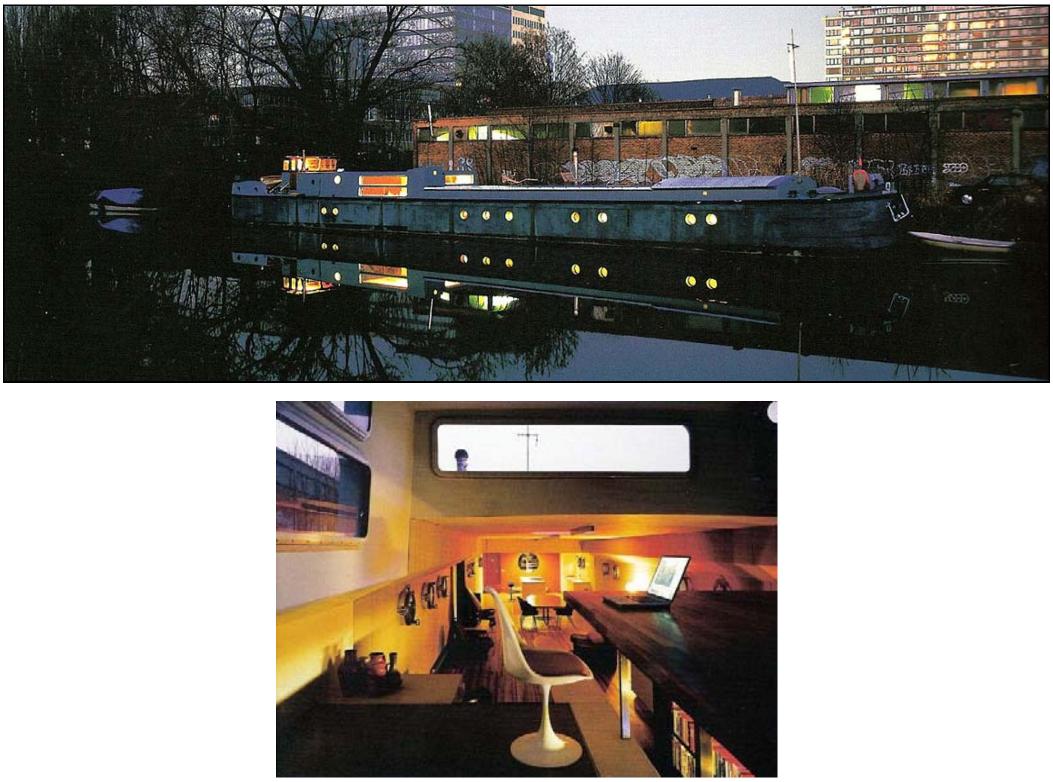

Figure 1. Barges are transformed to floating houses with modern interiors.

C. Burchard and F. Flesche, *Water House*, ed. F. Flesche (Munich: Prestel Verlag, 2005), 48-49.

The increase in the number of people who want to live on water led to proposals ranging from small settlements to floating towns designed by architects. The conversions of barges into floating houses can be indicated as responds to this request. Barges, which had been constructed for purely economic purposes as

[10] Burchard and Flesche, *Water House*, 13-14.

transportation of goods and offered little comforts, were transformed to houses with modern interiors (Figure 1). [11] "In reality, the floating city where people choose a dwelling on water rather than purchasing a house already exists." [12] That city is called *The World,* which is a ship, carries luxury vacation homes (Figure 2).

Figure 2. *The World.*

C. Burchard and F. Flesche, *Water House*, ed. F. Flesche (Munich: Prestel Verlag, 2005), 11.

Water as an architectural resource has been introduced in many kinds of ways from the time when the first piece of architecture was produced. Ice, liquid, and steam are three forms of water which are available to designers and certainly liquid is used most often among them. Yet, architecture is a part of the environment where it is commonly present therefore **ice** has also been tackled.[13] Many artists, architects, and engineers are interested in the idea of creating temporary structures from ice. The Inuit igloo is a dome of snow, which carries its own weight, can be stated as the first example of this idea. As in the case of *Icehotel* in Sweden (Figure 3), designed by Ake Larsson, the construction of the entire hotel repeats each year in early winter for 16 years. Because each springs ice melts and flows to river. [14]

[11] Ibid., 44-50.

[12] Ibid., 13.

[13] Moore and Lidz, *Water+Architecture*, 16.

[14] Burchard and Flesche, *Water House,* 122-130.

Figure 3. Interior of *Icehotel.*

C. Burchard and F. Flesche, *Water House*, ed. F. Flesche (Munich: Prestel Verlag, 2005), 132.

2.1 Background of Underwater Applications

So far, water has had a part in designing structures with different ways. According to Burchard and Flesche, the possible approaches to utilizing water can be classified as: fixed structures that are constructed on piles driven into sea bed, floating structures, structures constructing under water and structures of which construction ice (frozen water) was used.[15] Till now, all of them have been studied extensively by architects except for underwater structures. They have been mostly carried on different fields. Although underwater has always attracted people and designers with its unique characteristics and providing unusual experiences, architects did not deal with these structures until recent years. Namely, it started to be considered as a new medium by architects newly.

The **curiosity** about totally unknown subjects always lead human to struggle for preeminence. Exploring, employing and being part of underwater has been a **challenge** for human beings at all times. Therefore, throughout the history people searched for ways of dominating this mysterious world. As mentioned by Miller and

[15] Ibid., 17.

Koblick: “to live in and become part of the sea has long been a dream of humans, perhaps ranking second only to the desire to fly.” [16] They go on further by stating that, there were hundreds of different answers to the question “Why live in the sea?” Those answers were ranging from "because it's there" to "we must study the load-bearing characteristics of the seabed." In addition, “exploration, search for knowledge, adventure, and to become part of an alien world” were the common reasons. [17]

Myths and stories were written about the unknown depths of the oceans and submerged humans and vehicles beneath the water. These recordings, regardless of the reality in them, verified that underwater structures have been taken into consideration since early times. These stories also pointed out that underwater world should be explored to overcome the fear and to satisfy the curiosity about it. [18]

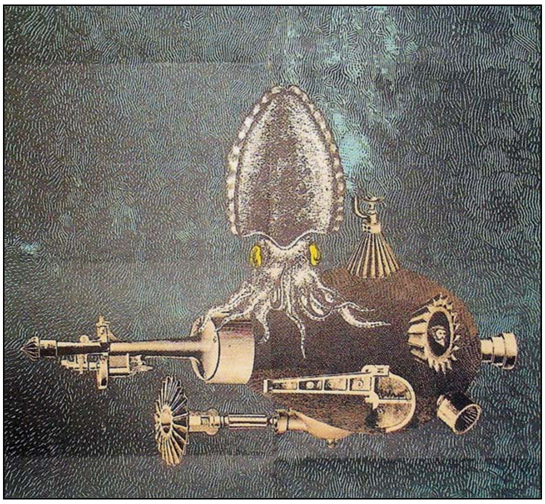

Figure 4. Illustration of *Nautilus.*

C. Burchard and F. Flesche, *Water House*, ed. F. Flesche (Munich: Prestel Verlag, 2005), 14.

[16] J. M. Miller and I. G. Koblick, *Living and Working in the Sea,* 2nd ed.(Plymouth: Five Corners Publications, Ltd., 1995), xiii.

[17] Ibid., 234.

[18] C. Ward, “One Fish, Two Fish, Red Fish, Blue Fish: A Journey into the Oceans” (Master’s Thesis, Dalhousie University, 1998), 12.

In 1870, the French writer, Jules Verne, published the science fiction classic *20,000 Leagues under the Sea*, which concerns the adventures of The Captain Nemo in a submarine, which is more advanced than any existed at that time, named as *Nautilus.* The Nautilus (Figure 4) was a self-sufficient submarine that obtained energy from salt water.[19] The story was an inspiration for subsequent underwater projects.

There has always been a mental and physical relationship between humans and oceans in addition to the curiosity and challenge to explore. Moreover, Carl believes that for man's survival into the 21st century, it will be necessary for man to make use of the great depths of the oceans for both military purposes and resources.[20] In the depths of oceans, there are reserves of mineral and food and energy resources, such as petroleum and natural gas. Besides, today the ¼ of petroleum is extracted from sea bottom using off-shore platforms.[21]

Technology increases the control of people among underwater. Along with technology, fascination has driven the people who study the oceans to produce the structures and instruments used for research of ocean and its depths. As a result, submarines and underwater habitats were constructed to meet these purposes concerning underwater.

Architects and engineers have always designed and sometimes were able to construct structures in "extreme conditions", such as space, ice and under water. Among them, designing structures for entertainment or accommodation under water can be stated as a challenge for designers and it became a race between architects and engineers especially during last years. In addition, it can be uttered as searching for new and different styles of buildings. On the other hand, in the future underwater structures may be essential. As noted by Burchard and Flesche, problems, such as the rapid and

[19] Burchard and Flesche, *Water House,* 15.

[20] C. T. F. Ross, "Design of Submarine," *University of Portsmouth*, http://www.mech.port.ac.uk/CTFR/concept/sub_1.pdf. Last accessed in February 2007.

[21] H. Özden and K. T. Gürsel, "Çok Amaçlı Kullanımlı Yarı-Batık Yüzer Ada Tesislerinin Tasarımı," *Gemi Mühendisliği ve Sanayimiz Sempozyumu*, (2004): 387. http://www.gidb.itu.edu.tr/staff/unsan/Kongre2004/41.pdf. (Last accessed in June 2007).

irregular increase in human population, disorganized urbanization, heavy traffic, drought, and exhausting of natural and energy source, led to search for **alternative accommodation areas**.[22] Within this perspective, space and underwater were stated as the potential habitats for human being in future.

"Space habitats" or space colonies are settlements in space which house large population in a rotating environment to achieve artificial gravity. [23] Since all the conditions in space colonies will be planned and controlled, they are likely to be less affected by disasters, such as overpopulation, ocean strikes or earthquakes that damage the Earth. Space race had begun in 1950s and the first space colony projects were introduced in 1970s. [24] At the same time with the studies about space, "new concepts of living on land, on water and under water" started to search. Furthermore, it was believed that exploring ocean was more significant than "space travel" and earth's oceans were suggested as a solution for the immediate problems of human kind instead of space. [25] Namely, it was more feasible to respond the problems of human kind in the future with underwater structures than space colonization. Besides, water should be considered first, since 70% of the earth surface is covered by water (Figure 5) and all aspects and possibilities of utilizing water should be taken into consideration by designers.

In 1960s, the desire to explore the oceans reached a high point. At the New York World's Fair of 1964, ideas of the colonization in space and under the oceans were presented to emphasize the increasing of global population and offer a response to it. As illustrated in Figure 6 *Futurama* was an **undersea city project**. [26]

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[22] Burchard and Flesche, *Water House,* 13.

[23] A. Globus, "The Design and Visualization of a Space Biosphere," http://alglobus.net/NASAwork/papers/RNR-91-018/lewisOnePaper.pdf, 1. (Last accessed in February 2007).

[24] A. Globus and B. Yager, "Space Settlements: A Design Study," *National Aeronautics and Space Administration (NASA)*, http://www.nas.nasa.gov/About/Education/SpaceSettlement/75SummerStudy/Table_of_Contents1.html. (Last accessed in February 2007).

[25] Burchard and Flesche, *Water House,* 114.

[26] Ibid., 16.

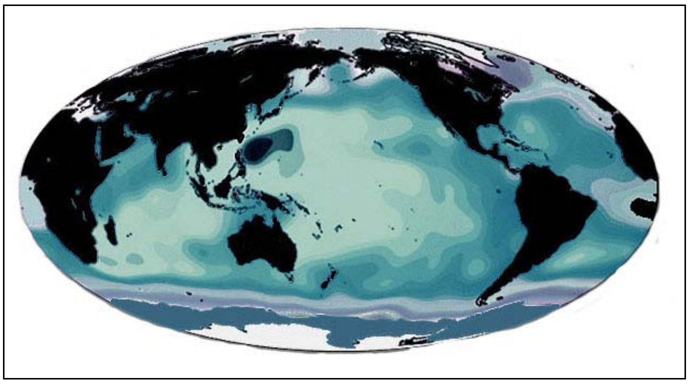

Figure 5. Water to land proportion on the surface of world.

Marine Science, "The World Ocean: Earth's Oceans,"
http://www.biosbcc.net/ocean/marinesci/01intro/woocean.htm. (Last accessed in June 2007).

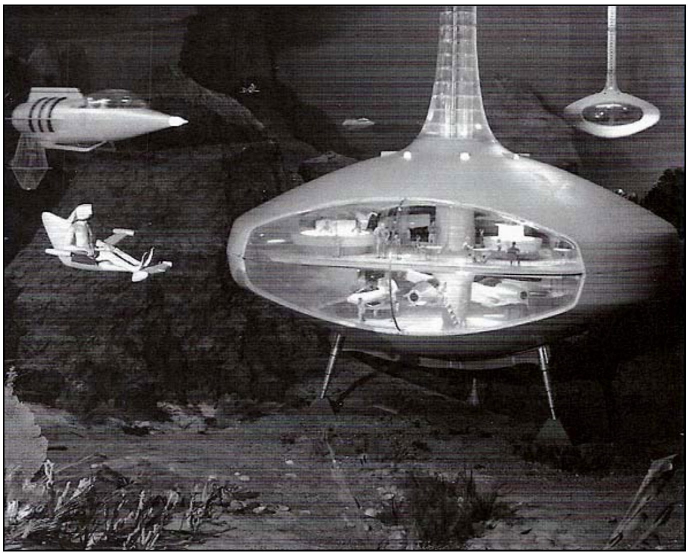

Figure 6. *Futurama undersea city.*

C. Burchard and F. Flesche, *Water House*, ed. F. Flesche (Munich: Prestel Verlag, 2005), 15.

Between 1950s and 1970s proposals for floating and underwater cities by architects were widely published in the architectural media. One of them is *Underwater City* as illustrated in Figure 7 by architect Warren Chalk designed in 1964. [27]

[27] S. Kaji-O'Grady and P. Raisbeck, "Prototype cities in the sea," *The Journal of Architecture* 10, no.4 (2005): 445-446.

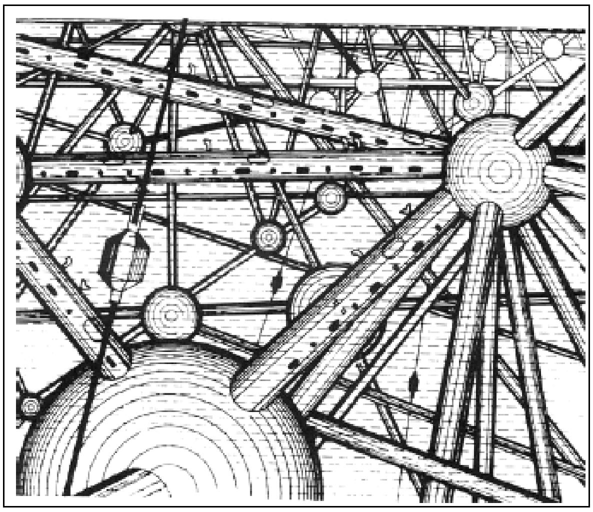

Figure 7. Underwater city by architect Warren Chalk (1964).

S. Kaji-O'Grady and P. Raisbeck, "Prototype cities in the sea," *The Journal of Architecture* 10, no.4 (2005): 447.

Those underwater city projects did not flourish because of the complication of implementation and testing of those projects. Besides, examples of marine architecture remain at the early stages of their technological development because innovation was accepted as time consuming and costly to achieve.[28] Accordingly, "ambitions for new societies in the sea have shifted to tourism and politically conservative plans for tax-havens."[29] Market-driven projects were started to propose instead of dealing with problems of earth. Small-scale projects started to proposed and built by individuals.

Utilizing underwater structure in tourism started with *Jules' Undersea Lodge*. Although the structure was an engineering standpoint and architectural requirements did not considered; the idea of "underwater hotel" was first achieved with this example. On November 1986, the undersea laboratory, *La Chalupa*, was converted into an underwater hotel that is known as "the word's first seafloor resort". Guests need to dive to enter the underwater hotel.[30] Figure 8 illustrates the layout of the

[28] Ibid., 449-453.

[29] Ibid., 454.

[30] Miller and Koblick, *Living and Working in the Sea,* 415-418.

hotel. One of the chambers began to use as “common room, containing a kitchen, dining and entertainment areas” and a 41inches (104 cm) window that provides view to exterior. The other chamber was divided into two to get private bedrooms that each has a 41 inches (104 cm) window. Wet room between these two cylinders served as an entrance with a shower and bathroom facilities. Entrances to the living quarters are provided through wet room.[31]

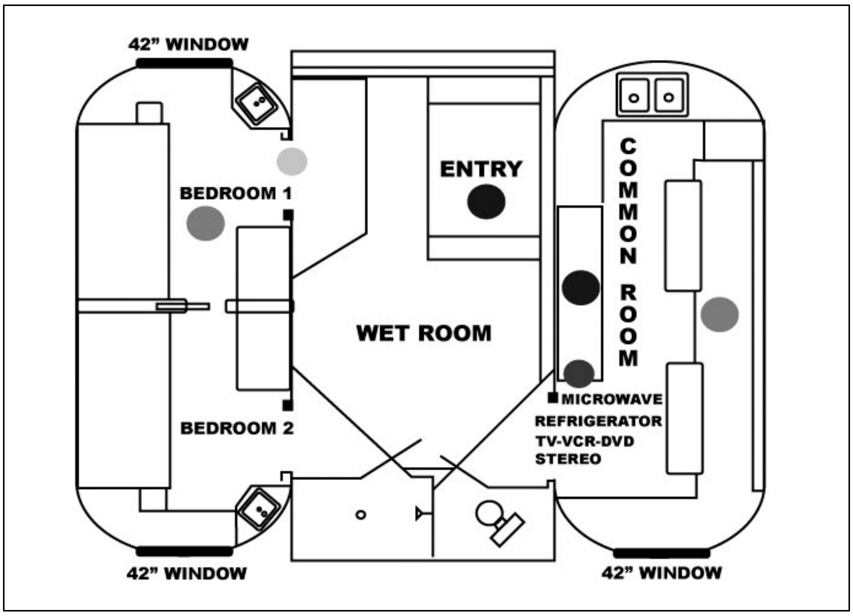

Figure 8. Layout of undersea lodge.

Jules’ Undersea Lodge, http://www.jul.com/frontpage.html. (Last accessed in June 2007).

2.2 Diving

In the history, the first attempt to explore and become a part of the underwater was **diving**. Therefore, the intention of discussion of diving in this study is not to explain diving techniques and requirements. On the contrary, it aims to mention the struggle of diving for human in order to highlight the importance of exploring the oceans, working and living in the sea. The journey of “being underwater” started from diving

[31] J. L. Straw, “Re: Master’s Thesis-Jules’ Underwater Hotel,” 9 November 2006, personal e-mail (10 November 2006).

and goes on by means of underwater structures such as habitats, submarines, restaurants, and hotels and possibly with the underwater cities in future.

Miller and Koblick explain the first attempt for being under the water with the story of two citizens of Eridu:

> The year is 2450 B.C. You're standing on the southern shore of the Persian Gulf watching two citizens of Eridu engage in their ancient trade. Glistening heads disappear from beside their boat. You see the wavering image of bodies through clear water as they sink. Less than 3 minutes later, they are gasping at the gunwale again, tossing their small harvest of pearl shells into the bottom of the boat, inhaling huge breaths for another brief visit to the sea bottom.[32]

The experiment of diving has been always a search for extended bottom time. This can be confirmed with the experience of Babylonian monarchy. "Although demand for pearls and jewels of all kinds has never been greater, the Babylonian divers are fighting the same physical limitations as their brothers and sisters around the world". "...divers forced away from their underwater work by the same barrier, bottom time depends on how long a diver can hold his breath".[33] Divers have coped with this barrier with using "breathing tubes of reeds, hollowed bones, air pockets in caves, and inverted buckets." The struggle of unlimited bottom time has continued throughout history.[34]

In the sixteenth century, Leonardo da Vinci created a device called "breathing tube" as shown in Figure 9. Miller and Koblick describe this device referred to MacCurdy in their book:

> A breastplate of armour together with hood, doublet, and hose, and a small wine-skin for use in passing water, a dress for armour, and the wine-skin to contain the breath, with half a hoop of iron to keep it away from the chest, if you have a whole-skin with a valve from

[32] Miller and Koblick, *Living and Working in the Sea,* 1.

[33] Ibid., 1.

[34] Ibid., 2.

> the "ball". When you deflate it, you will go to the bottom, dragged down by the sacks of sand; when you inflate it, you will come back to the surface of the water. A mask with the eyes protruding made of glass, but let its weight be such that you raise it as you swim.[35]

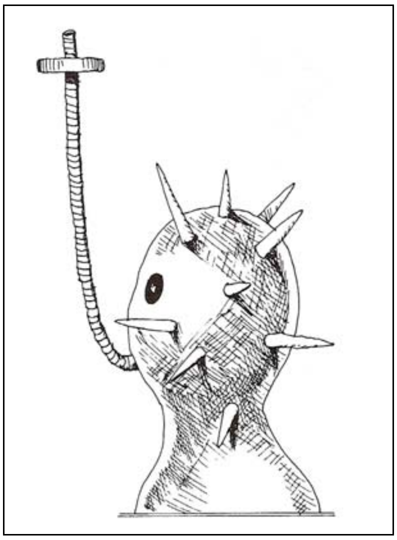

Figure 9. Breathing tube and underwater mask designed by Leonardo da Vinci.

J. M. Miller and I. G. Koblick, *Living and Working in the Sea,* 2nd ed. (Plymouth: Five Corners Publications, Ltd., 1995), 3.

During seventeenth and eighteenth centuries a prototype of the modern diving bell (Figure 10) was invented by Sir Edmund Halley and it was described by the inventor as:

> The bell I made was of Wood, containing about 60 Cubick Foot in its concavity, and was of the form of a Truncate-Cone, whose Diameter at Top three Foot, and at Bottom five. This I coated with Lead so heavy that it would sink empty, and I distributed the weight so about its bottom that it would go down in a perpendicular situation and no other.
>
> In the Top I fixed a strong but clear Glass to let in the light from above, and likewise a Cock to let out the hot Air that had been breathed: and below, about a Yard under the Bell, I placed a Stage which hung by three Ropes, each of which was charged with about one Hundred Weight, to keep it steddy. This machine I suspended

[35] Ibid., 2-3.

> from the mast of a Ship, by a Spritt which was sufficiently secured by Stays to the Masthead and was directed by Braces to carry it overboard clear of the Ship side, and to bring it again within board.[36]

"Air was provided by small barrels under the bell that could be opened when needed. Stale air was vented out of the top by means of a valve. Divers could even leave the bell wearing a helmet with an umbilical tube". The invention was called as the first diving system and its principles are still used in underwater habitats and platforms. [37]

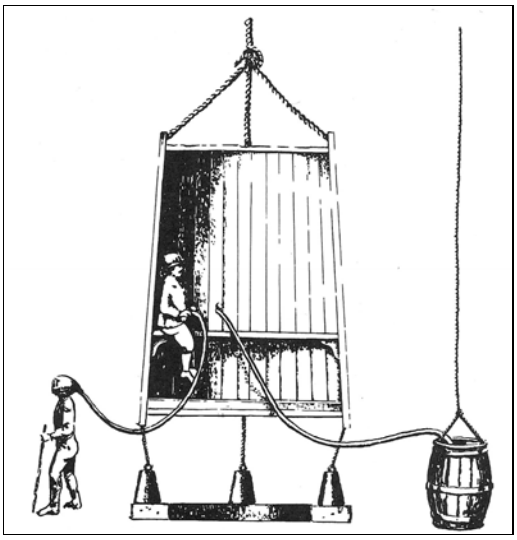

Figure 10. Halley's diving bell.

J. M. Miller and I. G. Koblick, *Living and Working in the Sea,* 2nd ed. (Plymouth: Five Corners Publications, Ltd., 1995), 4.

About 1819, an open diving dress was invented by Augustus Siebe which is consisting of "a waist-length jacket and a metal helmet". "Air under pressure supplied room the surface to the helmet by a force-pump could escape freely at the diver's waist." [38] In 1837, Siebe modified patented his open dress. The better version was "a full-length waterproof suit completely enclosing the diver except for the

[36] Ibid., 4-5.

[37] Ibid., 5.

[38] Ibid., 6.

hands", as described by Miller and Koblick referring to Martin. It is claimed that this suit has served as the origin for "modern deep-sea diving suit". [39]

In 1865, "a surface-supplied suit" was invented by Rouquayrol and Denayrouze. The diver wore a metal reservoir on his back and could remove the helmet to put the tube in his mouth and breathe directly when needed. A succession of diving breathing systems was developed in nineteenth century "to remove CO2 from exhaled air". Now a variety of substances are used to scrub the CO2 from exhaled air as a result of the work of many scientists. [40]

[39] Ibid.

[40] Ibid., 6-7.

CHAPTER 3

REVIEW OF FORMER UNDERWATER STRUCTURES

As explained earlier, underwater have been always a challenge and struggle for human and oceans had been utilized firstly for research, mining, sea farming, recreation, and military purposes. It was believed that “if humans were to survive on this planet, they would have to enter the underwater world and remain there to explore, observe, and harvest the wealth of the oceans.” [1] As a result, **submarines** and **underwater habitats** were generated to meet these goals. However architects used to design building on land and underwater is a new medium for them to design. Therefore, former structures, such as submarines and underwater habitats should be introduced in order to establish adequate knowledge for architects.

Designers can use technologies developed in other fields to design and construct in new environments. Accordingly, as mentioned by Kaji-O’Grady and Raisbeck, architects adopted technologies from the exploration, fishing, military and mining industries to understand and solve the threats to human existence under water.[2] Structures from engineering standpoint inspired architects to design under water. For that reason underwater habitats and submarines were studied briefly in the thesis.

It can be stated that the relation between human and underwater began with the first diving attempts in 2450 B.C. Increase in the time spend by divers on the sea bed, made essential survival shelters under the water called as underwater habitats. Underwater habitats are the first structures where human lived and was protected for weeks or months on the sea bed. Although at the beginning habitat projects were mere research facilities that support human life, by the time they were developed

[1] Ibid., 17.

[2] Kaji-O’Grady and Raisbeck, “Prototype cities in the sea,” 443.

with the considerations about human comfort. The applications of submarines are various and in literature there are many studies which were performed to analyze these structures in terms of design considerations. The difficulties and problems encountered and suggested solutions for both types of structures constitute references for architects through their applications under water.

3.1 Submarines

It is known that the opinion of traveling under the ocean inside a vessel have been existed for centuries. The early writings of man in history had been reported on this aim:

> Alexander the Great ventured below the waters of the Aegean Sea inside a glass barrel around 333 B.C. He was reported to have seen whales and deep-sea life on his underwater journey. The ancient Athenians used divers in secret military operations. Heroduotus (460 B.C.), Aristotle (332 B.C.) and Pliny (77 A.D.) mentioned attempts by others to build submersibles. [3]

Submarines are one of the inventions of human beings to explore the ocean bottoms of which surface area is about three times larger than earth's land area. A **submarine** is a specialized watercraft that can operate underwater at very high pressures. In common usage, submarine means a ship that operates above and below the surface. The undersea technology is already used for military purposes and submarine has played an important role in military affairs.[4] Together with military purposes, submarines have been used in various different fields, including submarine rescues, marine research, mining purposes and underwater cable and pipe laying.[5]

It is believed that one of the first attempts to build a vessel to submerge underwater was by Aristotle during 330s BC. However, this was only experimentation, and more

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[3] "Submarine History," http://www.globalsecurity.org/military/systems/ship/sub-history.htm. (Last accessed in January 2007).

[4] C. T. F. Ross, "A conceptual design of an underwater vehicle," *Ocean Engineering* 33, (Elsevier Ltd., 2005): 2087-2088.

[5] W. H. Lai, "Transient dynamic response of submerged sphere shell with an opening subjected to underwater explosion," *Ocean Engineering* 34, no. 5-6 (Elsevier Ltd., 2007):653.

realistic underwater vessel was built in 1776, by Bushnell. This vessel was in the form of the wooden spherical shell and called as *Turtle* (Figure 11). Turtle was the first military submarine driven by one operator.[6]

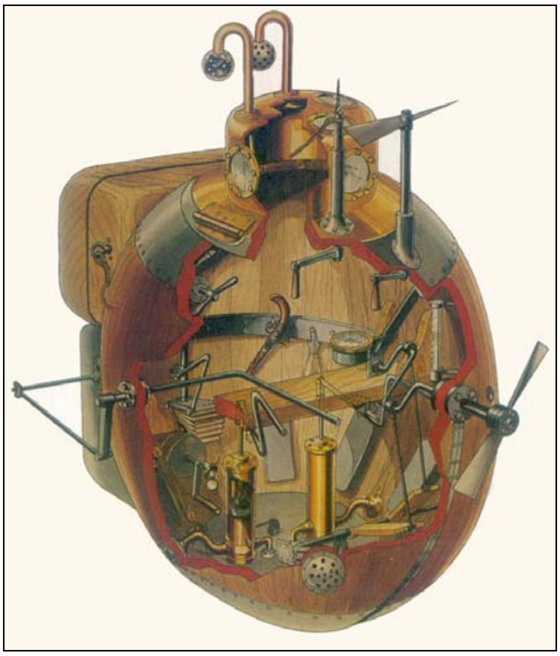

Figure 11. *Turtle*: The first military submarine.

http://www.heiszwolf.com/subs/plans/plans.html.(Last accessed in June 2007).

Throughout the years, many devices were tried for going under water. However being lack of a suitable power plant led most of the earlier designs to fail. The development of the battery and internal combustion engine made the submarine a reality as a practical vessel. Many different proposals and configurations were tried by inventors in different countries to become the first.[7]

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[6] Ross, "Design of Submarine," *University of Portsmouth*, http://www.mech.port.ac.uk/CTFR/concept/sub_1.pdf.

[7] R. Burcher and L. J. Rydill, *Concepts in Submarine Design* (London: Cambridge University Press, 1995), 11. http://books.google.com/books?hl=en&lr=&id=cN4cdjU5KTcC&oi=fnd&pg=RA2-PR11&dq=+%22Concepts+in+Submarine+Design%22+Burcher&ots=8kK90IIz4H&sig=Nek0lkI2cDG5nj3CDXrmopsg84w. (Last accessed in May 2007).

In 1899, the first “double-hulled vessel” was built by French.[8] Submarines became a weapon of war with the invention of steam engine in 1900 and played significant roles in both the major wars of this century. A major breakthrough in submarine design and construction was made by the Germans before the outbreak of the First World War.[9] As Carl quoted from Burcher and Rydill, “the U35 class of U-boats was a milestone in submarine design and construction. They used diesel propulsion while on the surface and resorted to battery power while submerged.”[10] The period following World War II brought great changes in submarine technology. The advent of nuclear power allowed submarines to stay submerged as “stealth weapons underneath the oceans”. Submarines achieved high speed with “teardrop hull” design.[11]

Apart from the fields explained above, submarines were also used for commercial purposes. In general most of the **commercial submarines** that have been constructed in recent years have been for oceanographic research, salvage rescue, cable repairing, sight seeing, and for checking and inspecting underwater structures.[12] Compared with military submarines there are very few commercial submarines. The tourist submarines become widespread because of the proven profitability and market differentiation. These submarines are comfortable and safe with large and panoramic view ports that provide fascinating scenes of the deep to the passengers. [13]

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[8] Ross, “Design of Submarine,” *University of Portsmouth*, http://www.mech.port.ac.uk/CTFR/concept/sub_1.pdf.

[9] “Chapter 10: Submarines and Submersibles,” *US Naval Academy*. http://www.usna.edu/naoe/courses/en200/ch10.pdf, 10. (Last accessed in January 2007).

[10] Ross, “Design of Submarine,” *University of Portsmouth*, http://www.mech.port.ac.uk/CTFR/concept/sub_1.pdf.

[11] “Chapter 10: Submarines and Submersibles,” US Naval Academy. http://www.usna.edu/naoe/courses/en200/ch10.pdf, 10.

[12] Ross, “Design of Submarine,” *University of Portsmouth*, http://www.mech.port.ac.uk/CTFR/concept/sub_1.pdf.

[13] A. Sezen, *The Underwater Hotel: Construction-Structure-Design* (Ankara: Öncü Basımevi, 2004), 17.

3.2 Underwater Habitats

Diving was the first attempt to explore the deep of oceans. As a result of diving attempts, divers become to stay on sea bed for longer times and began to feel the necessity of a protective shelter to survive under water. In other words, "... getting down has never been the problem. The challenge is staying down." [14] This was tackled by underwater habitats which provided refuge for human to work and live on the ocean floor.

The search for increased bottom time has stretched through thousands of years in human history. At the beginning, the time spend at the bottom was measured in minutes or hours however the opportunity of spending days and months on the sea floor become possible with **saturation diving** which is significant because once the tissues become saturated, the time to ascend from depth and to decompress safely, will not increase with further exposure to pressure. As noted by Miller and Koblick referring to Behnke, "the idea of remaining under pressure long enough to allow the blood and tissues to become fully saturated with breathing gases" was firstly used in order to improve the effectiveness and safety of tunnel and caisson operations. The utilization of saturation diving made it possible for air-breathing humans to live and work in the sea with only a single decompression at the end. [15] During saturation diving, air is the most common breathing gas since it is least expensive and is considered to be convenient to a depth of 50 feet (15.2 m) for saturation missions up to 7 days in length since. Other alternatives can be nitrogen-oxygen, or helium-oxygen mixtures.[16]

Divers faced with a problem which is called **decompression sickness** throughout the attempts for extending bottom time. There are many descriptions of decompression sickness by engineers and other interested observers in the literature. As noted by

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[14] T. Watson, "Sleep with the fishes," *Canadian Business* 77*, no. 3 (2004): pN.PAG,* http://web.ebscohost.com/ehost/detail?vid=2&hid=12&sid=e8710853-c2cd-4593-9a59-c1146879a751%40sessionmgr3. (Last accessed in May 2007).

[15] Miller and Koblick, *Living and Working in the Sea,* 13-16.

[16] Ibid., 193.

Miller and Koblick, Trigger made a description as "pain in the ears, nasal quality of speech, and joint pains" while Bert explained the reason of decompression sickness as "formation of nitrogen bubbles in blood and tissues and that the basic cause was increased partial pressure of gases in the breathing media"; and also "slow and gradual decompression" was suggested by him as the correct method to avoid decompression sickness. "A submersible **decompression chamber**" was built in 1928 to allow decompression to be carried out in relative comfort which increased the attempts to extend working depths.[17]

"Scuba divers joke that there are two ways to avoid decompression sickness, the rare but dreaded "bends": don't go down, or don't come up. In a sense, an underwater habitat is a way of making the latter option possible, at least for a few weeks."[18] Hernandez defines an underwater habitat as "a dwelling that allows human beings to live submerged underwater for long periods of time."[19] The **underwater habitats**, which were located on the sea bed, are research facilities where aquanauts[20] accommodate during their scientific researches, observations and training.

Underwater habitats are designed to operate in three fundamental modes. In the first mode they are completely open to ambient environment so the pressure inside is slightly higher than that of the surrounding water to prevent water from entering the habitat while locating on the seafloor. Second mode is valid during decompression. At this case, habitats are operated at pressures less than ambient pressure. As a third mode, underwater habitats can be operated in a combination of two modes, so that some chambers are depressurized and locked out. As long as a habitat will be used as a decompression chamber, it should be designed and constructed as a pressure vessel that withstands the external hydrostatic pressure.

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[17] Ibid., 7–10.

[18] S. Miller, "How an underwater habitat benefits marine-science," *National Oceanic & Atmospheric Administration*, http://www.uncw.edu/aquarius/about/sciamart.htm. (Last accessed in April 2007).

[19] F. A. Hernandez, "Underwater Farming Colonies: A new Space for Human Habitation," (Master's Thesis, University of Southern California, 2002), 33.

[20] Aquanaut is defined as "an individual who remains on the seafloor continuously for 24 hours or more" in *Living and Working in the Sea, by* J. M. Miller and I. G. Koblick, 28.

Undersea habitats were in many shapes, sizes, and even colors. Pure aesthetics, nationality, operating locality and the availability of used parts from local junk yards and factories can be stated as the reasons for such diversity. "Habitats have been built from cement mixers, boilers, rubber sheeting, molasses barrels, and railroad tank cars." [21] The shapes of habitats from 1965 to 1974 are illustrated in Figure 12.

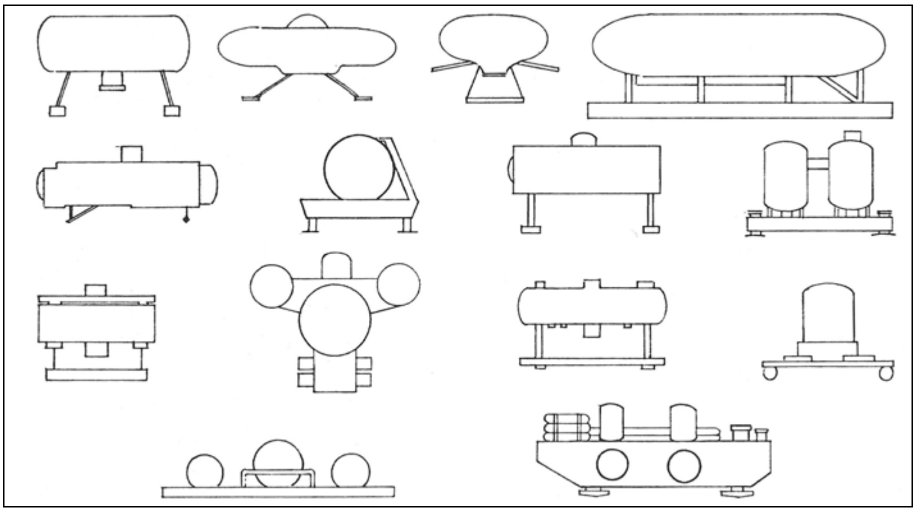

Figure 12. Representation of shapes of underwater habitats.

J. M. Miller and I. G. Koblick, *Living and Working in the Sea,* 2nd ed. (Plymouth: Five Corners Publications, Ltd., 1995), 142.

Before the first underwater habitat projects was performed, experiments on animals and humans were achieved to show the feasibility of staying underwater with saturation diving.[22] As a result of these laboratory experiments and open-sea saturation diving programs it was revealed that humans could live under the water. The purpose of the establishment and use of underwater habitats was to study human diving physiology in order to develop regular marine science research with a wide range of scientists. The first underwater projects were performed to demonstrate man's ability to live in saturation at depth, in comfort and safety. On the other hand, more recent ones have been performed for development in marine science by means

[21] Miller and Koblick, *Living and Working in the Sea*, 141.

[22] Ibid., 17-19.

of extending underwater observation which led to more precise observation and "longer-term data gathering." [23]

In the field of marine studies the focus was on the psychological effects of living for a long duration in a closed environment during a stressful voyage by means of saturation diving. Data, which were obtained from marine studies, were utilized by the NASA for "space program" since there are similarities between experiencing in a space shuttle and underwater habitats. [24] Therefore, NASA became a leading sponsor of the many programs. [25] Experiments were done in underwater habitats to observe reaction of human under space conditions. There are a lot of attempts of underwater habitat projects between 1962 and 1977.[26] Significant ones were mentioned briefly in this study to demonstrate the properties of these structures.

"Conshelf I" was carried out in 1962. During this program the first underwater habitat, which was a 8 x 17 feet (2.4x 5.2 m) steel cylinder, was anchored to the seafloor with huge blocks of pig iron and heavy chains at a depth of 32.8 feet (10 m). The structure had an entrance trunk in the floor that allowed easy access to the sea. [27]

"Conshelf II" accommodated five men for 4 weeks on the seafloor at a depth of 36 feet (11 m), was achieved in 1963. At the same time two men were to live for a week at a depth of 90 feet (27.4 m). This program had many purposes in addition to a larger crew, that can be listed by Miller and Koblick as "increase seafloor time; to demonstrate the feasibility of assembling livable, underwater dwellings; to show the possibility of using a variety of underwater tools; and to use a two-man, self-

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[23] U.S. Submarines Inc., "Habitats Sea Floor Concept," http://www.ussubs.com/habitats/floor_concept.php3. (Last accessed in April 2007).

[24] Burchard and Flesche, *Water House,* 106.

[25] U.S. Submarines Inc., "Habitats Sea Floor Concept," http://www.ussubs.com/habitats/floor_concept.php3.

[26] Miller and Koblick, *Living and Working in the Sea,* 53.

[27] Ibid., 30–31.

propelled deep sea submersible." [28] The main structure of Conshelf II is illustrated in (Figure 13).

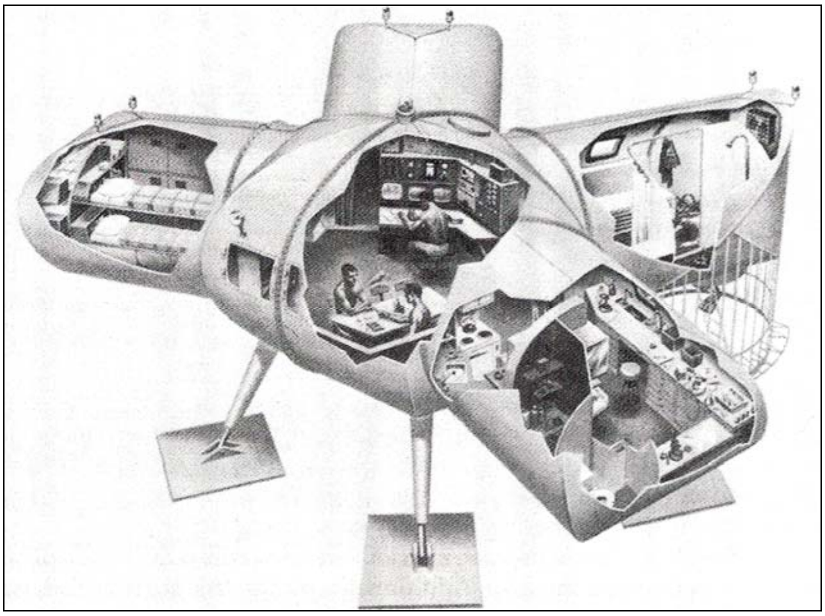

Figure 13. Conshelf II Habitat.

J. M. Miller and I. G. Koblick, *Living and Working in the Sea,* 2nd ed. (Plymouth: Five Corners Publications, Ltd., 1995), 34.

It was 34 feet (10.4m) at its widest point and consisted of a central section and four 4x8feet (1.2 m x 2.4m) cylinders. This structure contained sleeping quarters, a living and dining area, sanitary facilities, and a diving ready room. It rested on 7-feet long (2.1 m) telescopic legs, which allowed for leveling the structure on the seafloor. The advance of Conshelf II program was explained by authors with these words: "It was the first time humans actually lived on the seafloor with any degree of comfort, cooked their own meals and became part of the undersea environment." [29]

"Man-in-The-Sea II" was performed in 1964. The project's significance is to extend living and working capability to a depth of 400 feet (122 m). Although the previous projects had demonstrated that humans could live underwater for long

[28] Ibid., 33.

[29] Ibid., 34-36.

periods of time, they could not exceed the depth that could be obtained with surface diving techniques. The habitat, called SPID (submerged portable inflated dwelling), was a “8 feet (2.4 m) long by 4 feet (1.2 m) wide rubber bag mounted on a rigid steel frame” as demonstrated in Figure 14.[30]

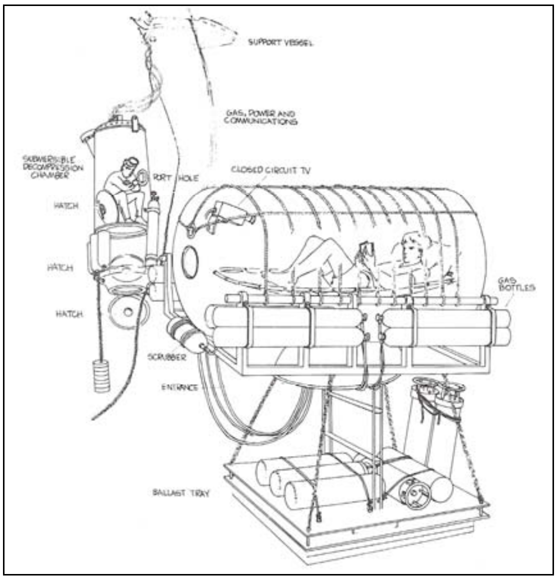

Figure 14. Sketch of Man-in-the-Sea habitat.

J. M. Miller and I. G. Koblick, *Living and Working in the Sea,* 2nd ed. (Plymouth: Five Corners Publications, Ltd., 1995), 39.

“Sealab I” was carried out in 1964 at a depth of 193 feet (58.8 m). The living space of the habitat was 24 feet (7.3 m) which was equipped with “bunks, lockers, laboratory equipments, environmental controls, refrigerator, a hot plate, an oven, a food locker, a shower, a toilet, air-conditioning equipment.” [31] A number of tasks were carried out by the aquanauts included “observing surrounding sea life, taking pictures, testing shark-attracting devices, and making specific marine biological observations”. The program was a major success because human had not ever worked and lived in the sea at so great a depth for so long according to authors.[32]

[30] Ibid., 37–40.

[31] Ibid., 42–43.

[32] Ibid., 45–46.

“Chernomor” was performed between 1968 and 1974. The basic pressure vessel was a cylinder 9.5 x 26 feet (2.9 X 7.9 m) with a depth capability of 164 feet (50 m). The habitat had five 8 inches (20.3 cm) portholes and general accommodations for a crew of four or five. The maximum self-sufficiency on the sea floor was considered in the design of the life-support system. Considerable effort was expended to make the habitat comfortable with providing hot water, carpets, a colorful decor, TV, and an adequate drying area designed to minimize dripping water in the living quarters. [33]

“Helgoland” was another project that was carried on between 1968 and 1976. The main body of the habitat was a 29.5 x 19.7 feet (9 x 6 m) cylinder (Figure 15) divided into two rooms. The living room was 8.2 x 8.2 feet (2.5 x 2.5 m) which also served as a decompression chamber. “This compartment was capable of withstanding an external pressure of 328 feet (100 m)”. [34]

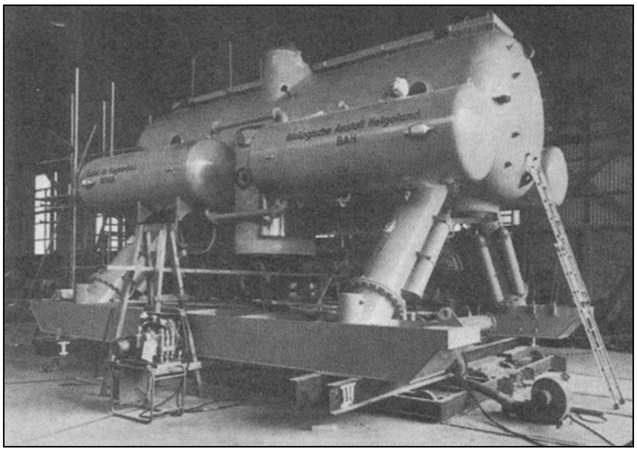

Figure 15. Helgoland.

J. M. Miller and I. G. Koblick, *Living and Working in the Sea,* 2nd ed. (Plymouth: Five Corners Publications, Ltd., 1995), 111.

“La Chalupa” was developed between 1972 and 1975 that was operated to depths of 100 feet (30.5 m). As other habitat programs, the main goal of the project was to

[33] Ibid., 98-105.

[34] Ibid., 110-119.

increase public awareness. In order to achieve that, the habitat was developed as “an undersea laboratory for use by scientists, training scientists in the use of undersea laboratory and saturation diving techniques”. Afterwards, it was converted into an undersea hotel. La Chalupa contains two 8 x 20 feet (2.4 x 6 m) cylindrical chambers and a 10 x 20 feet (3 x 6 m) wet room between them. The foundations of the structure are steel pipe hydraulic legs, holding the habitat 5 feet (1.5 m) off the bottom. The cylindrical chambers are used as control and living compartment. The wet room between the two cylinders provided a large, open utility area as well as serving as an entrance trunk for divers, a scuba fillings station, and diving gear storage area. The wet room also contained the toilet, and a freshwater shower. An artist's conception of La Chalupa is shown in Figure 16.[35]

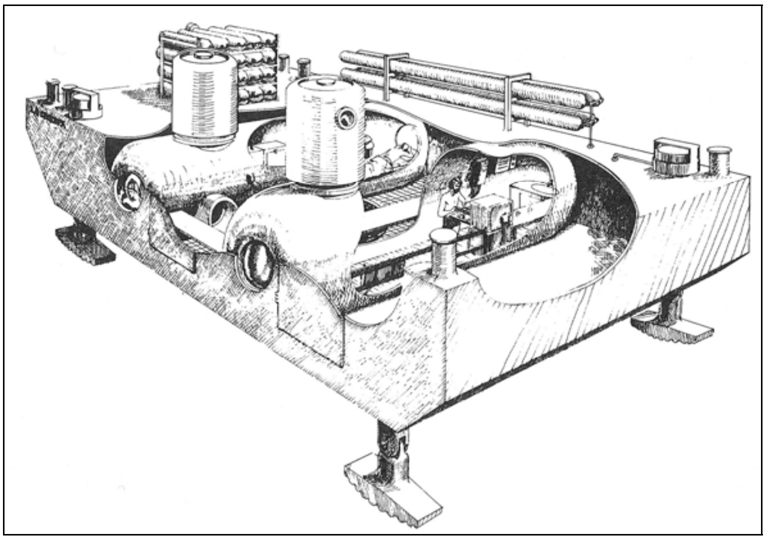

Figure 16. Sketch of La Chalupa habitat.

J. M. Miller and I. G. Koblick, *Living and Working in the Sea,* 2nd ed. (Plymouth: Five Corners Publications, Ltd., 1995), 158.

The habitat programs show the determination and devotion of human “to learn more of the sea and how to become a part of it”. As a result of those efforts, 65 habitats and numerous water welding habitats were built.[36] The impact of underwater

[35] Ibid., 123–126.

[36] Ibid., 382.

structures to marine life should be considered since they have carried on constructing. Within this perspective, Miller and Koblick explain that marine life is actually improved by the presence of underwater structure since the structures serve as artificial reef, providing shelter and substrate for marina animals. They claim that underwater structures do not distribute marine life on the contrary habitat and divers become the part of it very quickly and prove this idea by an example:

> The habitat quickly assumes the role of an artificial reef and attractant rather than a marine life repellent. Within minutes following emplacement of La Chalupa, each corner of the barge was claimed by some form of marine life that immediately took defensive action against all intruders, including the aquanauts. Within a few more hours, every nook and cranny was staked out as if the habitat had been there for years and the human intruders were accepted as part of this alien world.[37]

Furthermore, "the flow of air to the habitats constantly adds oxygen to the entire surrounding body of water, creating a symbiotic relationship between the technology of man and the beauty of nature". [38]

3.2.1 Problems with Ambient Pressure Habitats

In ambient pressure habitats occupants were exposed to the pressure caused physiological effects of living at depth. Saturation of tissues with nitrogen was stated as the major physiological problem when the occupants of habitats situated at a depth of more than 10 meters and stayed more than several hours. Decompression was required gradually when the tissue saturation occurred. According to the depth of habitat period of time for decompression procedure varied from 20 hours to several days. In addition decompression sickness can be occurred with "insufficient decompression or premature or accidental surfacing" and may lead to even death.

The expensive cost of gas mixtures, which should be supplied to occupants of habitats since normal air can not be breathed by them, is another problem related to

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[37] Ibid., 233-234.

[38] Straw, "Re: Master's Thesis-Jules' Underwater Hotel."

ambient pressure habitats. In addition there are other problems, such as "bone necrosis, inert gas narcosis, high pressure nervous syndrome, carbon dioxide poisoning, thermal problems and chronic ear infections" were mentioned.

As a result, development of one-atmosphere habitat system was introduced as a solution to the problems associated with ambient pressure habitats. It was also claimed that, "in a one-atmosphere habitat, the occupants remain at surface pressure regardless of the habitat's depth. Life in a submerged one-atmosphere habitat is no more stressful than life on the surface." [39]

3.2.2 Recent Technologies for Underwater Applications

The search for increased bottom time has carried with many attempts, humans truly become part of the undersea world since 1960's. The possibility of living safely and harmoniously in the sea has been demonstrated with the studies in laboratory and in over 60 seafloor habitat programs.[40] "However, the current trend is to remove the scientist from the water completely and use remotely operated vehicles and satellites to collect data, making the complex all-encompassing ocean an abstract of numbers and formulae." [41] According to Miller and Koblick, cost-effectiveness, insufficient fund of habitats, lack of mobility, and development of new technologies are reasons for the vanished of undersea habitats. [42]

Advances in science and technology offer alternative vehicles and equipments instead of underwater habitats which decrease the role of human for undersea applications. The "one atmosphere submersible vehicles" can be used for greater depths that permit divers to leave the vehicle added new dimension to undersea exploration. Divers have become to use "one atmosphere diving suits" which does

[39] U.S. Submarines Inc., "Habitats Superior One Atmosphere," http://www.ussubs.com/habitats/atmosphere_habitat.php3. (Last accessed in April 2007).

[40] Miller and Koblick, *Living and Working in the Sea,* 399.

[41] Ward, "One Fish, Two Fish, Red Fish, Blue Fish: A Journey into the Oceans", vi.

[42] Miller and Koblick, *Living and Working in the Sea,* 399-405.

not require decompression. Divers remain at “a single atmosphere or surface pressure environment” in these suits. Remotely operated submersible vehicles (ROVs) that incorporate manipulators, cameras, robots, are used to work and gather in the sea by a surface-control system.[43]

Machines operated from surface, from one atmospheric submersible vehicle or from one atmosphere diving suits are preferred especially in great depths (more than 300 foot (91.5 m). The undersea habitats can not compete with the unmanned systems because of the high cost of saturation diving systems and decompression. Nevertheless undersea habitats are still use in many fields. “Marine archeologists” use these structures for the excavation of shipwrecks and historical undersea ruins. Underwater habitats are used as “undersea laboratories” as research stations as mentioned before. At the same time these structures are used as “classrooms” in the wild in much the same manner as are polar, forest and desert stations”. [44]

[43] Ibid., 402-405

[44] Ibid., 405-407.

CHAPTER 4

DESIGN CONSIDERATIONS OF UNDERWATER STRUCTURES

> The peculiar demands of the marine environment meant that schemes for the sea, like those for outer space, needed to address questions of survival and technical resolution in ways that set them apart from the more conceptual proposals for benign terrestrial locales. The forces exerted upon structures under and on water are unlike those in terrestrial situations. The technologies for overcoming these challenges were born out of developments in engineering for aquatic structures and vehicles that came out of a broader push by governments and private corporations to inhabit, farm and mine the sea. [1]

Thus far, engineering have been mainly concerned with underwater structures. As a result, the pioneering examples are works of this discipline and the principles of underwater design should be asserted under the light of these former structures. From this concern, design considerations of submarines and underwater habitats were examined in order to constitute a background and guideline for architects. Certainly, underwater structures, such as restaurants and hotels, should be more than mere shelters and they should meet the requirements of space which is appropriate to accommodate or eat. However there are special parameters and limitations while designing in a totally different medium. Architectural approaches to underwater design did not entirely form from architectural origins. They were based on developments in naval and marine engineering. Therefore, in order to discuss the architectural aspects for underwater design, the characteristics of environment and design considerations from engineering standpoint should be examined and understood firstly.

[1] Kaji-O'Grady and Raisbeck, "Prototype cities in the sea," 447.

4.1 Form and Geometry of Underwater Structures

In general, buildings can stand in a safe manner with their structures that support and redirect forces and loads to ground. Referring to Onouye, it can be noted that: "to *structure* also means to *build* –to make use of materials in a way as to assemble an interconnected whole that creates space suitable to a particular function or functions and besides, to protect the internal space from undesirable external elements." [2]

Structures are facing wind force, effects of gravity, earthquake and dead and live loads on land. On the other hand, under water the primary force that structure should withstand is hydrostatic pressure depending on the depth of the sea or ocean. Intuitionally, it can be stated that, curvature forms (shell structures) are the most appropriate structures which resist the hydrostatic pressure by looking at nature. The form of man made underwater structures overlap with the shape and geometry of natural structures of underwater creatures. The sea urchin (Figure 17) is one of the most known examples, presented in depths of oceans, has a shell in which it preserves and survives.

Figure 17. Sea urchin.

http://www.brantacan.co.uk/gloscab.htm. (Last accessed in June 2007).

[2] B. Onouye, *Statics and strength of materials for architecture and building construction,* (Upper Saddle River, NJ: Prentice Hall, 2002), 2.

Certainly, underwater structures resist pressure by means of their form and geometry. Therefore the knowledge about form and geometry is fundamental for underwater design and should be studied apart since it governs other design considerations. Also, in this section fluid mechanics will be described briefly to gain an intuition and knowledge about the hydrostatic pressure. The characteristics of arch and shell structure, which can resist the hydrostatic pressure, will be discussed with the examples in practice. Accordingly fundamentals of arch dams will be analyzed to be able to understand the nature of their structural behavior. The form of habitats and submarine pressure hulls will be discussed to confirm in subject of the form and geometry of underwater structures.

4.1.1 Fluid Mechanics

Fluid mechanics is the sub discipline of continuum mechanics that is the study of the physics of continuous materials which take the shape of their container. The science of the study of forces and flow within fluids can be further subdivided into fluid statics and fluid dynamics. **Fluid statics** (also called **hydrostatics**) is the science of fluids at rest, and is a sub-field within fluid mechanics that interests in the conditions under which fluids are at rest in stable equilibrium.

Fluid pressure is the pressure at some point within a fluid, such as water or air. Fluid pressure occurs in one of two situations:

1. An open condition, such as the ocean, a swimming pool, or the atmosphere.
2. A closed condition, such as a water line or a gas line.

Pressure in open conditions usually can be approximated as the pressure in static or non-moving conditions (even in the ocean where there are waves and currents), because the motions create only negligible changes in the pressure. Such conditions conform to principles of "fluid statics"**.** The pressure at any given point of a non-moving (static) fluid is called the **hydrostatic pressure.** [3] The pressure is due to the

[3] B. R. Munson, D. F. Young and T. H. Okiishi, *Fundaments of Fluid Mechanics,* (New York: John Willey & Sons, 2002).

weight of fluid (which increases linearly with depth) pressing down only in the vertical direction. The depth is the only real determinant of hydrostatic pressure. Due to an ability to resist deformation, fluids exert pressure normal to any contacting surface. Additionally water pressure acts with equal magnitude in all directions when the fluid is at rest (static). This concept was known as *Pascal's law.* [4]

The pressure under water increases with depth, a fact well known to scuba divers. At a depth of 10 m under water, pressure is twice the atmospheric pressure at sea level, and increases by about 100 kPa for each increase of 10 m depth. One pascal (symbol: Pa) is equivalent to one newton per square meter (1 pascal (Pa) = 1 $N.m^{-2}$).

Objects can flow through or over fluids. This leads to the concept of **buoyancy**, the tendency of objects to float or sink in a liquid. This is due to the density of the object relative to the liquid.[5] The law of buoyancy was discovered by Archimedes of Syracuse and called as *Archimedes' principle.* According to that principle, the buoyancy is equal to the weight of the displaced fluid.Pascal's principle explains the buoyancy of a floating object. A solid body immersed in a fluid will have upward buoyant force acting on it. This force is equal to the weight of displaced fluid and enables the object to float or at least to appear lighter. This is due to the "hydrostatic pressure" in the fluid.[6]

4.1.2 Curvature Forms Withstand Hydrostatic Pressure

Surface structures are the structures consisting of thin, wide surfaces which function structurally mainly by resolving only internal forces within their surfaces. Tension surfaces and compression surfaces are types of surface structures. Compression surfaces must necessarily be more rigid than tension ones, because of the possibility of buckling. Compression resistive surface structures having curved forms are called shells. The egg, the light bulb, the plastic bubble are all examples of

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[4] "Physics of Liquids & Gases," http://www.vectorsite.net/tpecp_08.html. (Last accessed in January).

[5] Ibid.

[6] Munson, Young and Okiishi, *Fundaments of Fluid Mechanics.*

shells. Shells are suitable for both simple and complex geometries.[7] Shells are classified, for example cylindrical or spherical, according their geometry.[8]

Many fields and disciplines utilize "shell structures." Domes and other curved roofs of varied forms are examples of thin shell structures. "Pressure vessels and pipe work are key components in all branches of the chemical and petroleum industries." In the field of structural engineering, the use of tubular members was a striking advance to cope with an important problem which was to design compression members against buckling in the early development of steel. "Other examples of the impact of shell structures include water cooling towers for power stations, grain silos, armour, arch dams, tunnels, submarines, and so forth."[9]

The essential ingredients of a shell structure are "continuity and curvature". Shells are structurally continuous in the sense that they can transmit forces in a number of different directions in the surface. The strength and stiffness of a shell structure are related with curvature.[10] The stiffness and strength of curvature surfaces is originated from their resistance to deformations which tend to flatten them.[11]

Thin shells under compressive membrane forces are prone to buckling of a particularly unstable kind. "The rapid change in geometry after buckling and consequent decrease of load capacity leads to catastrophic collapse". [12] Go affirms that idea by stating that, the behaviors of curved surfaces are "nonlinear and sensitive

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[7] J. E. Ambrose, *Building structures primer,* (New York: Wiley, 1967), 93-96.

[8] "Shell Structures: Basic Concepts," http://www.colorado.edu/engineering/CAS/courses.d/AFEM.d/AFEM.Ch29.d/AFEM.Ch29.pdf, 29-3. (Last accessed in April 2007).

[9] Ibid**.,** 29-3-29-4.

[10] Ibid., 29-4.

[11] M. G. Salvadori, *Structure in architecture,* (New Jersey: Prentice-Hall Inc., 1963), 324.

[12] "Shell Structures: Basic Concepts," http://www.colorado.edu/engineering/CAS/courses.d/AFEM.d/AFEM.Ch29.d/AFEM.Ch29.pdf, 29-6.

to the buckling conditions”.[13] That behavior plays important role in the design of structures under uniform normal pressure. In practice dams, underwater storages and submarine can be listed as examples for this structure.[14] Figure 18 represents a cross section of a thin shell.

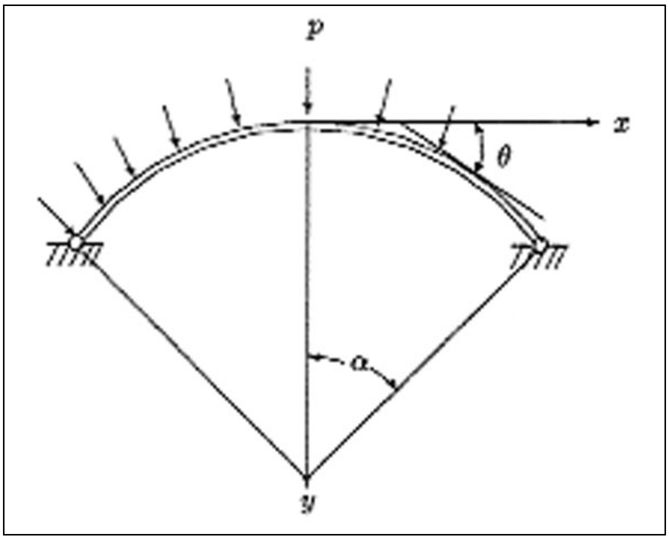

Figure 18. Load uniformly distributed around curved surface.

J. Go, “Buckling Arch under Normal Pressure,” (Ph. D. Thesis, Michigan State University, 2004).

Depending on previous studies Go mentions that; the flexural rigidity of the curved surface, the opening angle and the type of base (whether the base is clamped or hinged) affect the buckling pressure of the structure.[15]

As mentioned earlier, **arch dams** can be stated as an example for shell structure which resist hydrostatic pressure. Dams are barriers that built across a water course to hold and store water and can be classified into a number of different categories. Among these categories, arch dams are built in the form of a horizontal arch in

[13] J. Go, “Buckling Arch under Normal Pressure,” (Ph. D. Thesis, Michigan State University, 2004), abstract.

[14] Ibid.

[15] Ibid., 2.

narrow rocky canyons, transfer the massive load of the water to the canyon walls. [16] As explained by Yanmaz, "arch dams are thin concrete structures which carry most of the water thrust horizontally to the side abutments by arch action. A certain percent of water load is transmitted to the foundation vertically by cantilever action". Thus, it can be stated that "an arch dam is assumed to consist of series of horizontal arches and vertical cantilevers". [17] The applications of "the theory of elasticity" and "the theory of shells" are required for the structural design of an arch dam. It can be assumed that, the horizontal hydrostatic pressure near the crest of the dam is taken by arch action and transmitted to the sides, whereas the load is taken by cantilevers and transmitted to the foundation near the bottom.[18]

4.1.3 Survey of Form and Geometry of Underwater Structures

As noted by Ross, "the reason why pressure hulls are **curved** is that under uniform pressure, such a shape resists the load in membrane manner, rather similar to a rubber balloon resisting pressure when being blown up." [19] He goes on further by stating that, "the most efficient pressure vessel to contain uniform pressure is a uniform thickness spherical shell"; this is because such a vessel behaves as perfect membrane, and resists its pressure load with a uniform membrane stress, acting all over its surface." [20]

The pressure hulls of most submarines usually appear in the forms of thin-walled circular cylinders, cones and domes as shown in Figure 19.[21] On the other hand, as argued by Liang, "for deep-diving research, rescue or working submarines, spherical and elliptical pressure hulls which can bear a high hydrostatic pressure are frequently

[16] A. M. Yanmaz, *Applied Water Resources Engineering,* (A*nkara:* Metu Press, 1997), 29-41.

[17] Ibid., 51.

[18] Ibid., 52-53.

[19] C. T. F. Ross, "Design of Submarine," *University of Portsmouth*, http://www.mech.port.ac.uk/CTFR/concept/sub_1.pdf.

[20] Ibid.

[21] Ibid.

preferred.” [22] This can be explained with the fact that, the increase in the depth raises the hydrostatic pressure that the pressure hull should withstand.

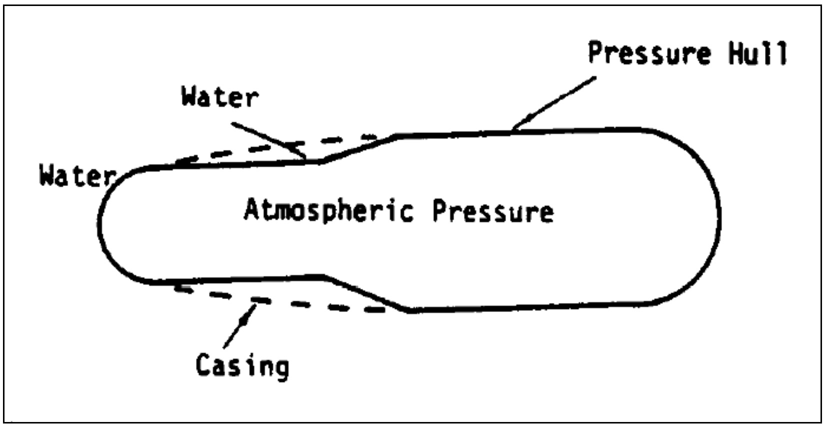

Figure 19. Submarine Pressure hull.

C. T. F. Ross, “Design of Submarine,” *University of Portsmouth*, http://www.mech.port.ac.uk/CTFR/concept/sub_1.pdf. Last accessed in February 2007.

The cylinder and sphere were verified as the most common shapes for undersea habitats and pressure vessels, by Miller and Koblick. Referring to Penzias and Goodman, they also emphasize that a cylindrical shape is more functional, however the features of a sphere was pointed as follow:

- A sphere requires the minimum shell area to enclose a volume.
- A sphere requires the least shell thickness to withstand the external pressure.
- Therefore, a minimum amount of shell material is required and the lightest possible pressure vessel can be achieved. [23]

The last item can be explained with a statement by Liang et al. According to them, cited from McKee, “the spherical pressure hull offers a better strength/weight ratio than a cylinder and cone.” [24]

[22] C. Liang, T. Teng and W. Lai, “A study of diving depth on deep-diving submersible vehicle,” *International Journal of Pressure Vessels and Piping* 75, no.6 (Elsevier Science Ltd., 1998): 447.

[23] Miller and Koblick, *Living and Working in the Sea*, 141-143.

Burcher defines the submarine pressure hull as the enclosed volume that is maintained at atmospheric pressure which is required for a manned submersible.[25] Submarines, which are in the form of spherical shell, are hydrodynamically unsuitable and difficult to dock; besides "thin-walled circular cylindrical shell" offers more interior space for crew and equipments. Nonetheless, still pressure hulls may be constructed as "thin-walled spherical shell" and a hydrodynamic hull surrounds this spherical pressure hull (Figure 20). The outer hull does not withstand any pressure difference, while the inner hull is subjected to water pressure since it has a normal atmospheric pressure inside as shown in Figure 21. In other words, it can be stated that most submarines have two hulls; internal is for holding pressure and external is for optimal hydrodynamic shape to streamline the submarine. [26]

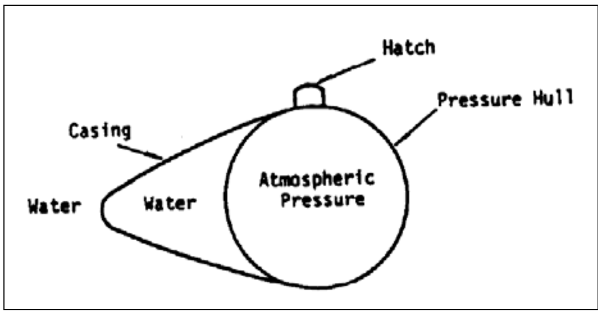

Figure 20. Spherical pressure hull.

C. T. F. Ross, "Design of Submarine," *University of Portsmouth*, http://www.mech.port.ac.uk/CTFR/concept/sub_1.pdf. Last accessed in February 2007.

As mentioned above, the submarine pressure hulls often constructed from various combinations of circular cylinders, cones and domes (Figure 22).[27] According to Ross, there are two kinds of failure modes related with pressure hulls.

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[24] Liang, Teng and Lai, "A study of diving depth on deep-diving submersible vehicle," 449.

[25] Burcher and Rydill, *Concepts in Submarine Design,* 71.

[26] Ross, "Design of Submarine," *University of Portsmouth*, http://www.mech.port.ac.uk/CTFR/concept/sub_1.pdf.

[27] C. Liang, W. Lai and C. Hsu, "Study of nonlinear responses of a submersible pressure hull," *Pressure Vessels and Piping* 75, (Elsevier Science Ltd., 1998): 132.

Under uniform external pressure, a thin-walled circular cylinder or cone can buckle at a fraction of the pressure to cause the same vessel to fail under uniform internal pressure. This mode of failure is known as shell instability, and it is undesirable because it structurally inefficient and one way of improving it, is stiffen the vessel with suitably spaced circular ring frames. If however, the ring stiffeners are not strong enough, the entire ring-shell combination can buckle bodily. This mode of a failure is known as general instability.[28]

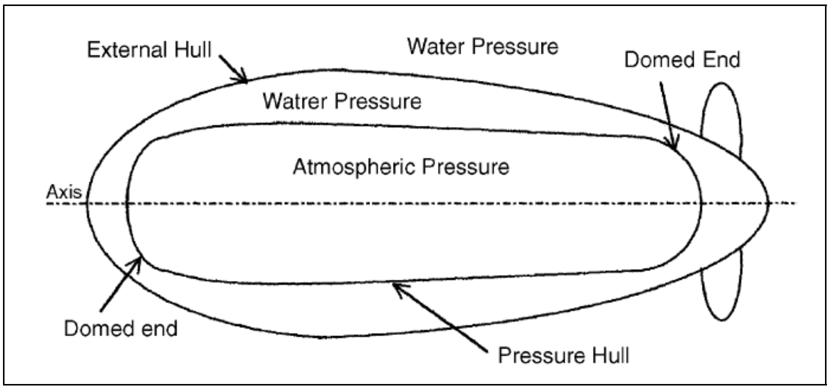


Figure 21. Outer hull and inner hull of a submarine.

C. T. F. Ross, "A conceptual design of an underwater vehicle," *Ocean Engineering* 33, (Elsevier Ltd., 2005): 2089.

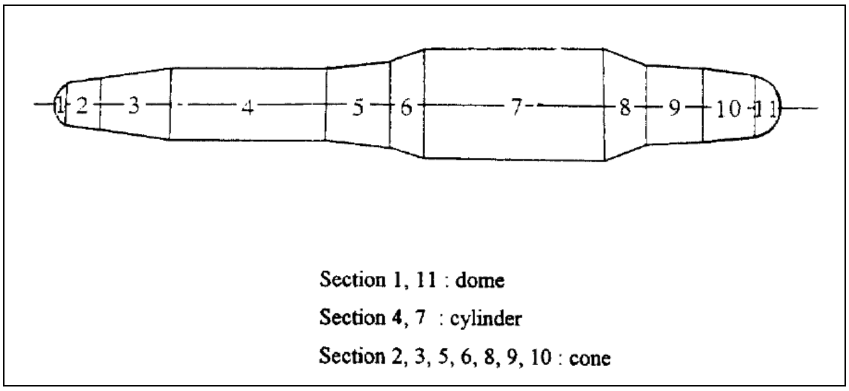


Figure 22. Submarine pressure hull structure.

C. Liang, W. Lai and C. Hsu, "Study of nonlinear responses of a submersible pressure hull," *Pressure Vessels and Piping* 75, (Elsevier Science Ltd., 1998): 132.

[28] C. T. F. Ross, "Design of Submarine," *University of Portsmouth*, http://www.mech.port.ac.uk/CTFR/concept/sub_2.pdf. (Last accessed in February 2007).

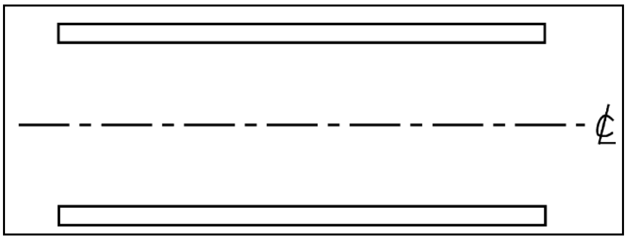
As clarified by Ross, “a ring-stiffened circular cylinder” is used frequently as the usual shape of a submarine pressure hull. Referring to the author the advantages of this structure can be listed as in the following:

- A ring-stiffened circular cylinder is able to resist the external hydrostatic pressure properly.
- Making the cylinder longer provides additional space inside the pressure hull.
- If a comparison is made between cylindrical and spherical form, a circular cylinder will be a better hydrodynamic form and also will be docked easier than a spherical form. [29]

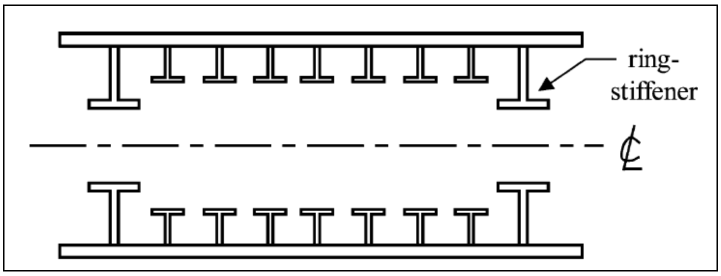
As stated above, a ring-stiffened pressure vessel is accepted as the common construction used for underwater pressure vessels. In addition, various types of constructions for cylindrical pressure hulls as shown in Figure 23 are mentioned by Liang et al. Firstly, “**pure monocoque constructions**” are used, **traditional ring-stiffened constructions** can be very efficient in resisting buckling, on the other hand cause some difficulties in “full-scale manufacture”. A **tube-stiffened construction** is an alternative to traditional ring-stiffened constructions; however, circumferential shell buckling often occurred in such constructions. **Corrugated hull wall construction** is another alternative design to the traditional ring-stiffened cylindrical pressure hull, which is declared as being structurally more efficient than the traditional ring-stiffened equivalent of the same volume and weight. In spite of this, such construction did not improve the structure’s bending stiffness. Recently, **sandwich structures** have been developed as a new design alternative for submersible pressure hulls. Sandwich hull constructions consisting of a pair of high-strength and stiff layers (facings), and a flexible layer (core) which is lightweight, have high stiffness and high structural efficiency. The structural efficiency of sandwich constructions depends on both the face sheets and its core configuration. [30]

[29] Ross, “A conceptual design of an underwater vehicle,”2089-2090.

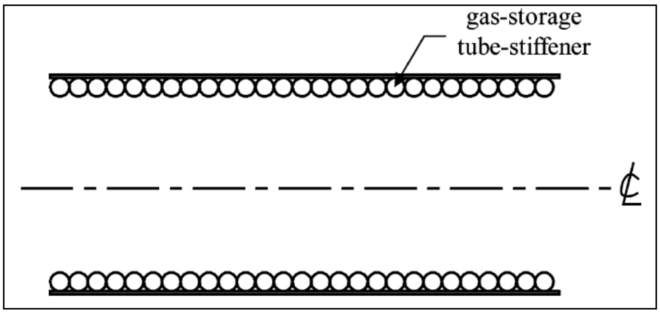
[30] C. Liang, H. Chen and C. Jen, “Optimum design of filament-wound multilayer-sandwich submersible pressure hulls,” *Ocean Engineering* 30, (Elsevier Science Ltd., 2003): 1942-1944.



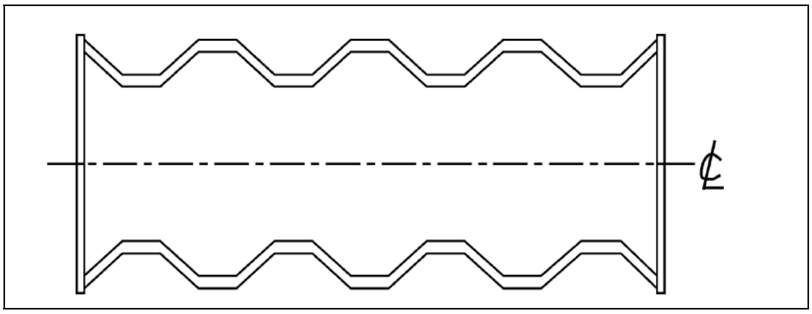
Pure monocoque metallic hull wall construction.



Ring-stiffened hull wall construction.



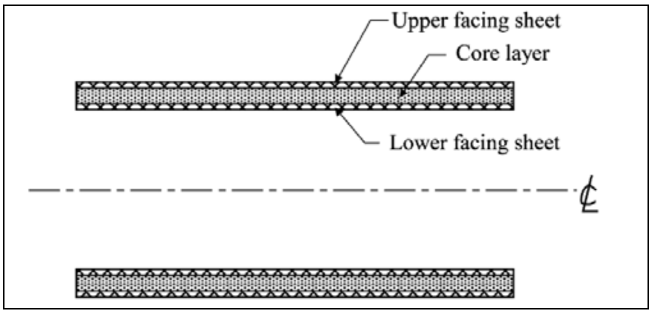
Tube-stiffened hull wall construction.



Trapezoid corrugated hull wall construction.

Figure 23. Various types of constructions for cylindrical pressure hulls.

C. Liang, H. Chen and C. Jen, "Optimum design of filament-wound multilayer-sandwich submersible pressure hulls," *Ocean Engineering* 30, (Elsevier Science Ltd., 2003): 1943-1944.



Sandwich hull wall construction

Figure 23. (Continued).

As mentioned in previous chapter, underwater habitats are structures that resist external pressure (during decompression) as well as internal pressure (on the sea floor). Miller and Koblick clarify two differences in the construction of a pressure vessel being designed for external pressure and for internal pressure although the basic engineering principles are same for both conditions. Within this perspective, they make the following statement quoting from Penzias and Goodman:

> For externally pressurized spheres, the basic membrane stress, remote from the collapse pressure, is one of compression. The applied load attempts to compact the vessel and push seams together. The failure mode, on thin walled vessels, is one of insatiability, in that initial deformations caused by the load lead to a shape which worsens the stress condition. In contradistinction, vessels under internal pressure try to bulge out, smooth corners and ease the stress conditions. [31]

4.2 Other Design Considerations

4.2.1 Materials

The materials used in underwater applications primarily should both be capable of withstanding "stress cycles" due to the external pressure and resist to corrosive effects of seawater.[32]

[31] Miller and Koblick, *Living and Working in the Sea,* 143.

[32] Ibid., 144.

In fact there are a variety of materials for underwater structures and parameters used in their selection. Citing to Busby, Miller and Koblick summarize these in Figures 24 that illustrates "a qualitative comparison of factors influencing the selection of materials for underwater use". [33]

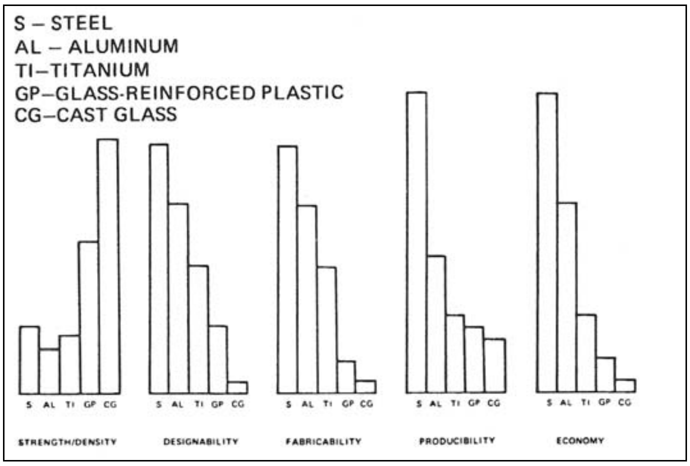


Figure 24. Parameters used in selection of material of underwater structures.

J. M. Miller and I. G. Koblick, *Living and Working in the Sea,* 2nd ed. (Plymouth: Five Corners Publications, Ltd., 1995), 144.

According to Ross, some of the required features of the materials used for underwater structures are:

- good resistance to corrosion
- high strength/weight ratio (the wall thickness should not be too large in order not to sink.)
- good sound absorption qualities
- material costs
- fabrication properties (easiness of manufacturing.)
- being convenient with pressure hull design
- fire protection (if material is susceptible to temperature.)

[33] Ibid.

- durability (operating life span of the material.) [34]

To date, **steel, aluminum, or titanium** are used conventionally in the construction of pressure vessel and "each material has advantages and disadvantages with respect to such factors as corrosion resistance, fatigue, fracture resistance, ductility, and yield strength." [35]

HY80 is the most commonly used of the **high strength steels**, which is also commonly used for commercial applications, such as pressure vessels, storage tanks and merchant ships.[36] So far, high tensile steel is mostly used in the constructions of submarine pressure hulls and the main problem is the increase of wall thickness among large diameters. As a result the weight of vessel rises and the vessel becomes to have no reserve buoyancy. [37] The main criteria for use of steel are suitability to galvanize or paint use and welding property. [38]

Aluminum alloys are preferred as a construction material because of their availability, low cost and being easy to fabricate. The main disadvantage of this material is being vulnerable to corrosion when used in mixed structures because of their chemical properties (being anodic to most other structural alloys). [39] **Titanium alloys** have a better strength/weight ratio than aluminium alloys and are ideal to be used for the pressure hulls of large submarines. On the other hand titanium alloys are 5.5 times more expensive than aluminium alloys and it is an important disadvantage for this material. [40]

[34] Ross, "A conceptual design of an underwater vehicle," 2098.

[35] Miller and Koblick, *Living and Working in the Sea,* 144.

[36] Ross, "A conceptual design of an underwater vehicle,"2099.

[37] C. T. F. Ross, "Design of Submarine," *University of Portsmouth*, http://www.mech.port.ac.uk/CTFR/concept/sub_4.pdf. (Last accessed in February 2007).

[38] Sezen, *The Underwater Hotel: Construction-Structure-Design,* 35.

[39] Ross, "A conceptual design of an underwater vehicle," 2099.

[40] Ibid., 2100.

Additionally, **composites** and **complex alloys** may also be used together with traditional materials.[41] For example, fibre-reinforced polymer composites are began to use in naval structures instead of conventional shipbuilding materials, such as steel and aluminium alloys to improve the operational performance and reduce the ownership cost. [42] Many engineering structures, such as aircrafts, spacecrafts, submarines, automobiles, trucks and rail vehicles, require more stiff and strong materials with less weight. These requirements increase the use of composite materials. [43] Composite materials are widely used for marine applications and are employed in many forms. Referred to Mouritz et al., Liang et al. declare that, the advantages provided by using composites in pressure hulls over the use of steel include reduced weight, superior corrosion resistance, improved hydrostatic strength, and reduced electrical and magnetic signatures. [44] According to Mouritz et al., improvements in design, fabrication and mechanical performance of low-cost composites raise the use of composites for large naval craft and submarines.[45]

As mentioned by Miller and Koblick, the excellent strength qualities under hydrostatic pressure loads, excellent durability in seawater, and being appropriate for the construction of complex shapes lead the **concrete** suitable for underwater structures.[46] Differently from the underwater concrete structures in fresh water or river, such as foundations of bridges, the structures built in aquatic or marine environment are showing important loss of durability. "Antiwashout-underwater

[41] Ibid., 2098.

[42] A. P. Mouritz et al., "Review of advanced composite structures for naval ships and submarines," *Composite Structures* 53, (Elsevier Science Ltd., 2001): 21-22.

[43] D. M. Frangopol and S. Recek, "Reliability of fiber-reinforced composite laminate plates," *Probabilistic Engineering Mechanics* 18, (Elsevier Ltd., 2003): 119.

[44] C. Liang, H. Chen and C. Jen, "Optimum design of filament-wound multilayer-sandwich submersible pressure hulls," 1944.

[45] Mouritz et al., "Review of advanced composite structures for naval ships and submarines," 21-22.

[46] Miller Koblick, *Living and Working in the Sea,* 144.

concrete is employed in aquatic environment and is increasingly applied to concrete structures in marine environment rather than fresh water or river." [47]

Providing views to exterior is important in submarine and underwater habitat design. In order to achieve this, view ports with transparent material were provided in these structures. The extensive use of transparent **acrylic plastic** (polymethly methacrylate) in deep submersible and aquarium applications were seen during the last 20 years. Important characteristics of the material are being strong and transparent. [48] Another plastic material which was stated as promising for future use is **polycarbonate** with its superior resistance to impact. It was recomended for structures in shallow depths.[49]

Different approaches also can be found from the study of previous underwater habitats. One of them is using "a synthetic fabric, inflatable hull". This technique can maintain strength if only the internal pressure slightly greater than the ambient water pressure. [50]

4.2.2 Corrosion and Protective Coatings

Corrosive action of seawater on metals is a very old problem thus prediction and compensation can be simple. Although, even properly selected metals are exposed to attack by organisms which can quickly damage protective coatings. The basic process of corrosion can be described as an electrochemical reaction between the environment and metal1ic surfaces. [51] In the marine environment, corrosion has been comprehensively studied and a lot of data gathered related to corrosion rate. The diffusion rate of oxygen through layers of rust and marine organisms governs mainly

[47] H.Y. Moon and K. J. Shin, "Evaluation on steel bar corrosion embedded in antiwashout underwater concrete containing mineral admixtures," *Cement Concrete Research* 36, (Elsevier Ltd., 2006): 521.

[48] L. B. Jones, "Re: Thesis-Poseidon Underwater Resorts," 1 November 2006, personal e-mail (3 November 2006).

[49] Miller and Koblick, *Living and Working in the Sea,* 155–156.

[50] Ibid., 146.

[51] Ibid., 148.

the attack of submerged surfaces. The amount of damage is independent of water temperature on the other hand industrial pollution increases the corrosion rate.[52]

Underwater structures remain submerged in salt water, consequently the prevention of corrosion through the use of protective procedures and coatings should be thought carefully. The immense reduction of corrosive action of seawater can be achieved by the proper use of protective coatings. A properly selected paint system will both protect metal surfaces and decrease annual maintenance costs. There are various types of nonmetallic coatings, such as oil-base paints, epoxies, and inorganic zinc.[53] As most common international practice, steel will be first galvanized and than in order to improve the strength painted with one of the various submarine paints. In order to protect the metal construction from moss and bacteria, "antifouling paints", which are composed of epoxy resin or rubber, are used. [54]

4.2.3 Ports and Windows

Pressure hulls with openings, for example manholes, view ports, and so on, are generally used in ocean and aerospace structures. In underwater habitats ports and windows are served to permit scientific observation, "increase the joy of living in the sea" and mainly establish relationship with environment. The necessity of openings is verified with the following statement by Miller and Koblick: "to live in the sea and not be able to observe the neighborhood and its residents is unacceptable to most aquanauts".[55]

However, ports and windows in pressure vessel lead design problems concerning "hull integrity".[56] "The openings are particularly important for underwater vehicles that must withstand hydrostatic pressure since casualties are unavoidable when a

[52] Ross, "A conceptual design of an underwater vehicle," 2089-2099.

[53] Miller and Koblick, *Living and Working in the Sea,* 149.

[54] Sezen, *The Underwater Hotel: Construction-Structure-Design*, 40.

[55] Miller and Koblick, *Living and Working in the Sea*, 155.

[56] Ibid.

catastrophic failure of a view port in a pressure vessel containing people is occurred."[57] It can be asserted that, closed surfaces are rigid in theory. Yet, it is not usually possible to make completely closed structural boxes in practice and such opening can be strengthened to provide structural continuity. The edge of the hole is reinforced to compensate for the presence of the hole. The amount of reinforcement that is required depends on the size of the hole.[58]

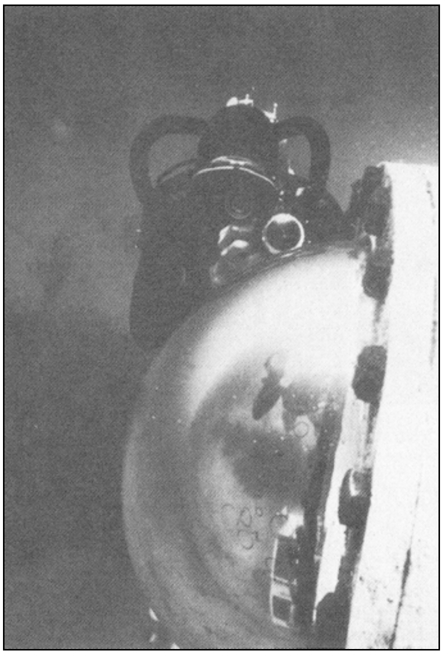


Figure 25. Hemispherical port provides 180 degree view.

J. M. Miller and I. G. Koblick, *Living and Working in the Sea,* 2nd ed. (Plymouth: Five Corners Publications, Ltd., 1995), 157.

There were variety in the shapes and sizes of windows of underwater habitats. Various configurations, for example flat, conical, hemispherical, or combinations of these were used in the ports. Glass and mostly acrylic plastic were used for these openings. To demonstrate, acrylic hemispherical ports were used to provide a viewing angle nearly 180 degrees in Tektite habitat (Figure 25). The largest ports

[57] Lai, "Transient dynamic response of submerged sphere shell with an opening subjected to underwater explosion," 653.

[58] "Shell Structures: Basic Concepts," http://www.colorado.edu/engineering/CAS/courses.d/AFEM.d/AFEM.Ch29.d/AFEM.Ch29.pdf, 29-5.

used for undersea habitats were flat acrylic plastic ports, 42 inches (106.7 cm) in diameter and 4 inches (10.2 cm) thick which were designed to withstand both internal and external pressures. [59]

4.2.4 Insulation

Insulation should be considered in underwater structures not only to control heat loss and gain, but also to prevent condensation. Particularly, insulation is essentially required to minimize the condensation on interior walls and overhead surfaces irrespective of the ambient water temperature. Namely, as explained by Miller and Koblick, “insulation has been found to be desirable, even in tropical areas, to reduce interior condensation while on the seafloor and for cooling when the habitat is on the surface”. [60]

The type and amount of insulation required for the hull of an underwater structure is related with the feature of the surrounding environment as any other structure. Insulation may be applied to the inside or outside of a habitat. As long as placed inside, the risk of fire also must be considered. [61]

4.2.5 Habitability and Atmospheric Control

Habitable can be defined as "suitable to live in."[62] Environmental control systems are required to sustain a breathable atmosphere and to maintain the internal climate within a ‘comfort zone’ to ensure habitability.[63] The critical aspects of atmosphere

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[59] Miller and Koblick, *Living and Working in the Sea,* 155–156.

[60] Ibid., 169-171.

[61] Ibid., 171.

[62] Ibid., 210.

[63] Ross, “A conceptual design of an underwater vehicle,” 2093.

control are **oxygen supply**, **carbon dioxide removal** and **trace contaminant control** with atmosphere analysis to ensure the safety of environment.[64]

The oxygen supply systems that were used in submarines are high pressure (gas) oxygen storage, liquid oxygen storage, electrolytic oxygen generation with water, and chemical oxygen sources.[65] The use of electrolytic generators from water is probably the best method since a supply of water is not a problem. Besides the system does not have any problems concerning safety and operational.[66]

The air we breathe contains about 0.03% of carbon dioxide. Such a level will be difficult to maintain and the required effort to so do, will not be justified. Therefore, the carbon dioxide control system should be capable of maintaining the carbon dioxide level below that which will impair mental and physical performance. There are many systems currently in existence on both spacecraft and submarines and these depend on absorption and adsorption. [67]

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[64] C. T. F. Ross, "Design of Submarine," *University of Portsmouth*, http://www.mech.port.ac.uk/CTFR/concept/sub_5.pdf. (Last accessed in February 2007).

[65] Ross, "A conceptual design of an underwater vehicle," 2094.

[66] Ross, "Design of Submarine," *University of Portsmouth*, http://www.mech.port.ac.uk/CTFR/concept/sub_5.pdf.

[67] Ross, "A conceptual design of an underwater vehicle," 2095.

CHAPTER 5

ARCHITECTURAL APPROACHES TO UNDERWATER DESIGN THROUGH CONTEMPORARY EXAMPLES

As explained before, technologies of other fields were utilized by architects to design and construct underwater projects. So far, structures that were constructed for different purposes inspired architects. Moreover, some of the realized projects were produced by engineers who were experienced in submarine and acrylic tunnel design. [1] On the other hand, one of the main objectives of architecture is to provide human a comfortable living area by means of meeting their requirements. Namely, architecture creates spaces for people. This purpose of architecture should be valid in any medium, that is say underwater. Therefore architectural aspects for the design of underwater structures should be taken into consideration and discussed with an indication on their difference from terrestrial ones.

In the design of underwater structures it should be intended to meet a set of design goals for a livable space. In other words, criteria for a livable space should be defined and applied according to underwater conditions. These criteria can be listed as:

- Keeping the inside pressure equal to the surface pressure.
- Establishing adequate technical systems to meet human comfort.
- Meeting all the physiological requirements of occupants.
- Providing convenient lighting to the space.
- Offering an adequate transportation system to carry people to the structure or proposing suitable entrances according to the whole project.
- Offering view to exterior to link interior space with environment.
- Ensuring the safety.

[1] These examples and their designers will be pointed out in the following pages.

In designing and construction of a terrestrial building, **environmental forces**, such as geographical location of site, topography, plantations, climate, orientation to the sun and prevailing winds, should be considered by architects. These factors affect the form of building, articulation of enclosure, relationship to the ground and lay out of interior spaces. [2] Additionally, architecture create spaces according to the conditions, for instance to make a shelter against a cold wind is totally different from making a shelter against breeze.[3] Therefore, forces and conditions of the environment should be well comprehended. Architects can be supposed to deal with unfamiliar limitations and problems in different mediums and new attitudes will be adopted in new environments. It is obvious that, the design, construction, and maintenance of an underwater structure should be different from the terrestrial ones. **Resisting to hydrostatic pressure** and **waterproofing** are the major obstacles and limitations for underwater structures. These factors should be taken into consideration in the first phases of design since they affect all architectural decisions and solutions from form and geometry to decisions concerning materials and technical systems.

5.1 Architectural Design Parameters for Underwater Structures

In previous chapter, design considerations of underwater structures from engineering standpoint were discussed to constitute a basis. This section will point out the considerations which should be thought in design of underwater structures by architects. To achieve that, parameters will be defined and interpreted according to the conditions and limitations of the environment in order to set the fundamentals for architectural approaches to underwater design. These parameters can be defined as:

1. Project Type.
2. Form and geometry.
3. Degree of enclosure.
4. Entrance space and access.

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[2] F. D. K Ching and C. Adams, *Building Construction Illustrated*, 2nd ed. (New York: Van Nostrand Reinhold, 1991).

[3] S. Unwin, *Analysing Architecture,* 2nd ed. (New York: Routledge, 2003), 111.

5. Dependency of structure (land-depended or autonomous).
6. Safety
7. Selection of site.
8. Lighting.
9. Use of color.
10. Construction and Assembling.

5.1.1 Project Type

According to the project type underwater structure may be linked with other terrestrial buildings or may be independent. At the first phases of design process, the decisions about the "physical and operational relations" with others parts and shore should be made and all the solutions and required systems will be designed accordingly. Mainly two alternatives can be thought:

- The underwater structure can be a part of complex which was located on land.
- The underwater structure itself can constitute the whole project. In this case, there may be also two alternatives:

    1. All functions can be housed by underwater structure.
    2. There can be a structure over water level that houses other functions. The two parts (over water and submerged), which have no relation by means of structure, can be link with staircase or elevators.

5.1.2 Form and Geometry

"In art and design, form denotes the formal structure of a work, the manner of arranging and coordinating the elements and parts of a composition so as to produce a coherent image."[4] **Form and geometry** of underwater structures are formed by hydrostatic pressure which is the primary struggle for underwater structures. This

[4] F. D. K. Ching, *Architecture: Form, Space, & Order*, 2nd ed. (United States of America: John Wiley & Sons, Inc., 1996), 34.

concept has been studied for years by engineers; and curvilinear forms such as sphere, cylinder and cone were affirmed as possible basic forms that resist under water. On the other hand, for underwater habitats there were examples with non-curvilinear forms from which limited views can be provided to exterior. As a result, different space qualities were achieved with different forms.

If the designer is familiar with the behavior of the basic shell structures had been used in underwater design, she/he can propose new forms and geometries with her imagination and knowledge. New spaces according to the functional requirements can be achieved with the manipulation of the basic forms, such as sphere, cylinder, cone and dome. Intersection or combination of these basic forms can be introduced as some alternatives among various ones. The structural capacity and behavior of these new geometrical configurations should be analyzed with considering other properties in further studies.

5.1.3 Degree of Enclosure [5]

The space must have a barrier that separates interior and exterior. Barriers can be combined to form an **enclosure**. **Openings**, such as windows, doors or view ports, define a link between two separate spaces through barriers. Properties of an opening determine the qualities of space, for instance light, view and degree of enclosure. [6] In the case of underwater structures, the amount of enclosure should be decreased.

Certainly, providing maximum transparency and view is a more appropriate approach for the nature of underwater design. Moreover, it can be stated that one of the main objectives of underwater designing should be establishing relations with underwater. “Architecture always depends on things that are already there.” [7] Namely, as the problems, the potentials and peculiarities of the environment should be recognized and besides utilized.

[5] Heading was cited from *Architecture: Form, Space, & Order*, by F. D. K. Ching, 168.

[6] Ching, *Architecture: Form, Space, & Order*, 166.

[7] Unwin, *Analysing Architecture,* 62.

The submerged structures are able to provide distinctive experiences for people, such as observation of underwater world and integration with the environment. This can be achieved by means of view ports and transparent shell elements. Such openings in structure offer view from the interior space to the exterior in order to establish visual relationships with surrounding. It can be suggested that transparent materials, which have enough strength to resist hydrostatic pressure, can be preferred to enclose interior space in underwater structures to achieve maximum view and relation with environment.

5.1.4 Entrance Space and Access

The way of access to underwater structures and design of entrances places should be considered at the conceptual design phase. Human can directly reach the entrance space which is under water by “scuba diving”. However desirability of this approach can be questioned, due to the fact that it will not be preferred by visitors. Various alternatives of access can be achieved according to the location of entrance space. Entrance space can be provided on land or over water.

First, entrance space can be designed on land. It can be constructed as an individual building or provided in other building of complex. After that the access to the underwater structure will be trough **horizontal, vertical** or **inclined tunnels** according to the level and locations of the structures. Steps, escalators, ramps or moving platforms can be provided in tunnels (Figure 26). Certainly a second entrance area can be provided under water.

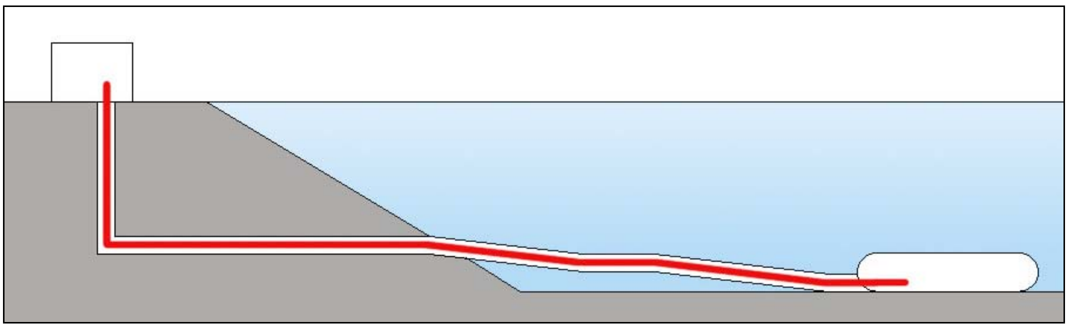

Figure 26. Entrance space was provided on land.

Secondly, entrance space can be designed over the water level. People can reach this space by motorboats or via a land bridge. Afterwards, the access to the underwater structure can be through **vertical tunnels.** Probably, elevators or staircase will be provided in tunnels (Figure 27).

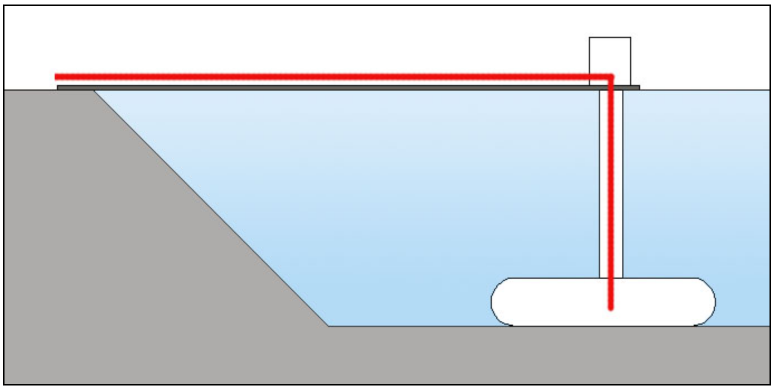

Figure 27. Entrance space was provided over water.

These tunnels can also be used to transport air, power and water from land to the submerged structure. As suggested by Sezen the tunnels can be divided into two parts. [8] Technical equipments and pipes can be located one section while people move in the other part.

5.1.5 Dependency of Structure (Land-depended or Autonomous)

The living conditions in underwater structures should be designed to be similar to those on land. Against environmental conditions architecture suggests systems for human comfort. The following ones should be considered and designed with engineers:

- First of all, to survive a breathable atmosphere should be achieved. Therefore **air supply system** (oxygen supplement and removal of carbon dioxide) is essential.

[8] Sezen, *The Underwater Hotel: Construction-Structure-Design,* 26.

- **Electrical system** is vital to survive underwater since all other systems depend on it. The system supplies power for lighting, heating, operation of electrical equipments and appliances. Therefore, uninterrupted electric power should be provided to underwater structures.
- **Mechanical systems** are required to provide **comfort-zone** conditions for occupants. These systems include the heating, cooling, ventilating, and air-conditioning equipments used to control the comfort factors such as air temperature, relative humidity of the air and air motion. [9] These systems may show differences in underwater structures because of the special requirements of an enclosed atmosphere.
- **Water supply** is needed for occupancy, climate control, and fire protection. For human consumption and sanitation a potable water supply is essential.
- System for **waste management** is another issue that should be provided for collection and removal of waste water and organic waste. The disposal of perishable and nonperishable hard waste from kitchens and rooms should also be taken into consideration.

Underwater structure can be either **land-depended** or **autonomous (self-sufficient)**. The decision relating to this issue should be made in the beginning of design phase.

i. Land-depended

The structure can be **land-depended** and typically would have normal air supplied from the surface through a pressure resistant pipe. Likewise, power and water can be provided to the structure from the land. Energy, water and air transported via **tunnel** will be distributed in the underwater structure. If the underwater structure is a part of a complex, the resources of the complex can be shared by the submerged part. In addition, an independent technical unit can be constructed on land that is linked to city network. Afterward, all necessary equipments for mechanical and electrical systems can be transported from land to submerged structures. According to Sezen, electric power can be transported by "submarine power cables" from land. Fiber

[9] Ching and Adams, *Building Construction Illustrated*, 11-2.

optic wires can also be placed for communication purposes, such as telephone, internet and TV connections.[10] Similarly, wastes can be transmitted to the land for necessary applications.

Electric can be provided from land through tunnels. However energy storage namely "electric generators" should be positioned under water in emergency conditions. Similar to electric power, although water can be supplied from land storage should be thought in order to deal with the break down of the supply system.

ii. Autonomous

Alternatively, the structure can be completely **autonomous** with its own diesel generators, water makers, satellite communication, sewage treatment plant and other equipment to form a complete, self-contained system anchored off-shore. [11]

5.1.6 Safety

There might be a crack in the submerged structure caused by an unpredictable event or other problems. Therefore the safety of occupants is vital that must be though and provided in underwater design. Emergency exits and entrance for divers to interfere should be designed. Safety places, as shelter in terrestrial buildings, can be proposed in underwater structures. Small submarines may be placed in critical areas to transfer the people inside the structure to land. For damages which are able to repair on the sea bed the pressure-resistant door, as in the habitats, will be locked automatically.

5.1.7 Selection of Site

In the word the underwater structures are located in special sea beds which contain special underwater flora such as coral reefs and various sea creatures to display them as a scene. Therefore, after decision was made to design an underwater structure,

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[10] Sezen, *The Underwater Hotel: Construction-Structure-Design*, 45.

[11] U.S. Submarines Inc., "Habitats Sea Room Activity Center," http://www.ussubs.com/habitats/activity_center.php3. (Last accessed in April 2007.)

required study should be performed through the region where project will be constructed.

On the other hand it can be stated that, for beginning the challenge of achieving structures under water may be more significant that the quality of site. From this perspective, initially underwater structures can be constructed as a part of existing buildings without respect to characteristic of sea bed, for example a hotel complex on island or near the sea.

5.1.8 Lighting

Light is a fundamental element in architecture which serves two primary objectives: illuminating a task and creating a mood. The lighting system should provide sufficient illumination for the performance of visual tasks, such as dining, reading and watching.[12] The sun is a rich source of **natural light** for the illumination of forms and spaces in architecture. [13] Besides, this daylight has psychological benefits as well as practical utility. [14] However, underwater spaces may not be utilize day light as terrestrial ones. Therefore lighting system should be appropriate to compensate with **artificial light** which is natural light that is provided by manufactured elements. As a matter of fact, interior light should be meeting the requirements of comfortable living. All activities can be carried out like on land without any obstruction.

"Light is an essential ingredient to establish an appropriate emotional environment for the activity that will take place there. Light can have a strengthening or reinforcing effect in creating a suitable psychological setting." [15] Therefore, the cold color and impression of the water can be softening with appropriate lighting

[12] Ching and Adams, *Building Construction Illustrated,* 11-24.

[13] Ching, *Architecture: Form, Space, & Order,* 171.

[14] Ching and Adams, *Building Construction Illustrated,* 1-13.

[15] S. Kubba, *Space Planning for Commercial and Residential Interiors* (United States of America: McGraw-Hill, 2003), 198-199.

solutions. On the other according to the architectural decisions the impact of the water can be emphasized.

Exterior lighting can be used mainly to demonstrate the surrounding for underwater structures. Occupants and visitors of the underwater structures can observe the underwater creatures with the use of the exterior lighting. Turning on the exterior lights attract the surrounding animals' attention and cause them come nearer that provide interesting sights and an unusual experience for the ones in the structure.

5.1.9 Use of Color

Generally color can be used to emphasize the character of the space or change it. In underwater design color can be utilized to handle the disadvantage of the environment on perception of space quality. Warm colors can be preferred to balance and deal with the cold blue color of the water. The underwater restaurant, *Red Sea Star,* can be demonstrated as an example for this approach (Figure 28). To balance the bluish aquatic light, a range of color from yellow to orange and red were chosen.

Figure 28. Use of color in Red Sea Star undersea restaurant.

C. Burchard and F. Flesche, *Water House*, ed. F. Flesche (Munich: Prestel Verlag, 2005), 111.

5.1.10 Construction and Assembling

As mentioned before architects should be aware of the limitations and potential of the environment. Besides, adequate knowledge about construction and assembling is required. The most appropriate techniques should be utilized. For instance, the structure can be constructed in sections that can be easily transported later assembled on the site and finally submerged. Unrealistic design and requests will cause loss of time and cost. Therefore, architects should contact with the persons experienced in the construction of this type of structure in order to make efficient and appropriate design according to this new environment.

5.2 Study on Contemporary Underwater Structures

Developments in undersea technology lead architects to search for new styles. Besides investors have being demanded places that provide more than basic functions and different experiences to their customers. From this perspective, undersea resorts and restaurants have started to design during recent years. Sezen defines the underwater hotel as "a different type of lodging where the people who wonder about the bottom of the sea and who like to experience adventure prefer to stay. Such a search for difference has occurred in every era and there has been a quest and curiosity towards unknown." [16]

As mentioned before, the concept of underwater design has been a race between architects and engineers in order to become "the first in the world". At present, there are realized projects which can be stated as architectural approaches in underwater design. In this section of the thesis, the intention is to make a comparative study on these contemporary examples. The design and construction process of these structures has differences from the conventional structures on land. These aspects, which should be considered for the overall success of the project, were discussed in detail in previous section from the architectural point of view. At this point the

[16] Sezen, *The Underwater Hotel: Construction-Structure-Design,* 25.

applicable ones will be evaluated focusing on the examples. This evaluation follows the outline, which was set in the section 5.1.

The selected examples, which are an undersea resort, a hotel room underwater, and two underwater restaurants, will be analyzed and compared. They were designed by both architects and engineers and can be stated as the first architectural approaches to underwater design.

5.2.1 Poseidon Undersea Resort [17]

Poseidon Undersea Resort is a "permanent sea floor one-atmosphere resort" of which construction continues in a private island in Fiji. The structure will be situated on **40 feet (12.19 m)** below the water level and the interior of the resort remains at surface pressure at all times. The underwater structure is a part of a complex which includes 20 bungalow resort and various entertainment functions. The structure was linked to the shore through a service tunnel in addition to the main access via a dock.

Figure 29. View from inside of the suite.

L. B. Jones, "Re: Thesis-Poseidon Underwater Resorts," 1 November 2006, personal e-mail (3 November 2006).

[17] Data about the project was cited from document in pdf format sent by e-mail by L. B. Jones, "Re: Thesis-Poseidon Underwater Resorts."

It was designed by engineers of *U. S. Submarines, Inc*. which is a company active in design and construction of civil submarine for 13 years. The resort is scheduled to open on May 14, 2008. Figure 29 demonstartes the structures through a view from inside of the resort.

i. Form and Geometry

There are mainly two kinds of units in different sizes for different facilities combined with a tunnel those function as corridor. The underwater structure consists of a central passage and suites, service areas and two main units which were attached to it, as demonstrated in plan view layout (Figure 30). The main ax (central passage) is a steel cylinder in 2.5 m diameter. Suites and service areas are in the form of a submarine. Main units, which are at the end of the ax, have curvilinear wall and a dome made of from acrylic. The suites measure 10m x 5.1m and comprise 51m² of floor space. They made from steel plates and acrylic plastic in curvilinear form (Figure 31). The wall structure was 25 mm steel plate and followed the same curve as acrylic in 100 mm thick. The acrylic window sections were set into a steel frame which was 3.05m in length around the curve and 1.75m wide. The floor consists of two sheets of 50 mm steel plate set 600 mm apart.

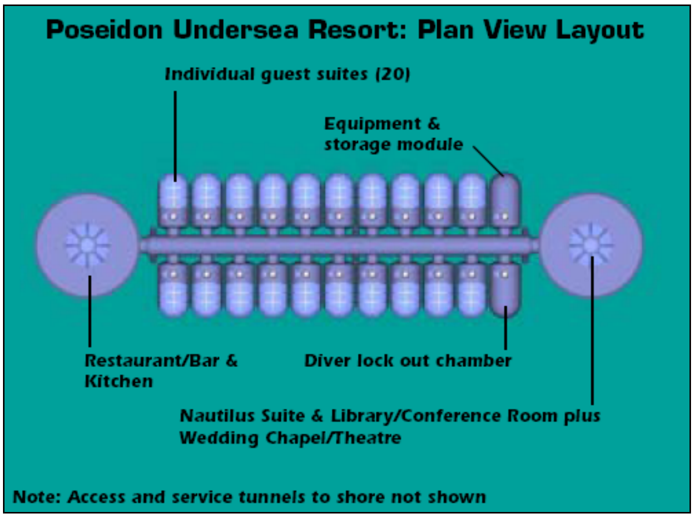

Figure 30. Plan view layout.

L. B. Jones, "Re: Thesis-Poseidon Underwater Resorts," 1 November 2006, personal e-mail (3 November 2006).

ii. Degree of Enclosure

One of the important achievements of this project is to maximize the undersea viewing. Using curvilinear surfaces with transparent material led to provide view to exterior. The image of expected view from suite, which was displayed by designers, is illustrated in Figure 32. The design of resort used the advantage of acrylic plastic, that is, acrylic provides strength as well as transparency in curved surfaces. The 70% of surface of suits is transparent. As shown in Figure 31, to provide privacy acrylic was used only overhead and front part of suits.

Figure 31. Use of steel and acrylic for suite modules.

L. B. Jones, "Re: Thesis-Poseidon Underwater Resorts," 1 November 2006, personal e-mail (3 November 2006).

Figure 32. The image of expected view by designers.

L. B. Jones, "Re: Thesis-Poseidon Underwater Resorts," 1 November 2006, personal e-mail (3 November 2006).

ii. Entrance Space and Access

Entrance space was designed over water on pier. People came through motorboat and reach to the foyer and reception area under water by an elevator in a vertical tunnel. There is another tunnel for service facilities as shown in Figure 33.

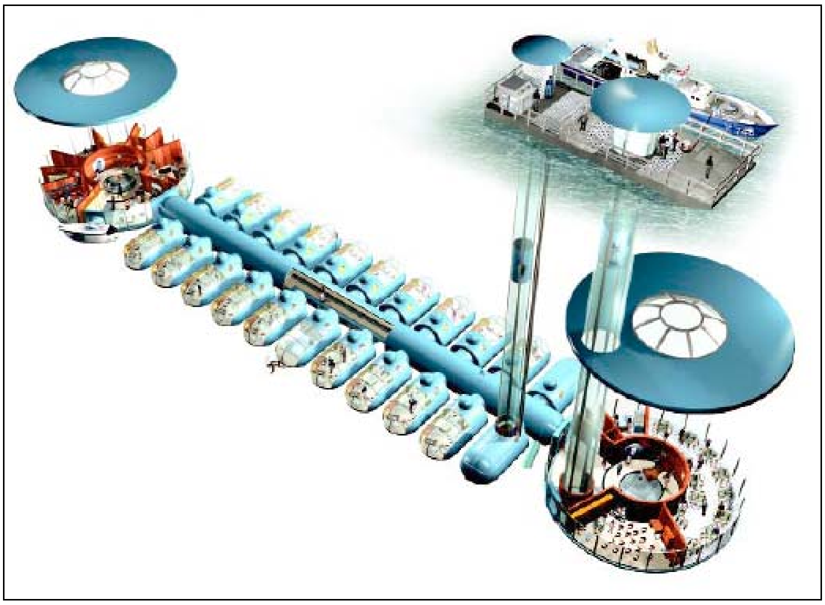

Figure 33. Access to underwater structure.

L. B. Jones, "Re: Thesis-Poseidon Underwater Resorts," 1 November 2006, personal e-mail (3 November 2006).

iv. Construction and Assembling

Project were designed and constructed as modules that attach to the main axes. Figure 34 demonstrate the placement procedure for the suite module. Each suite has an integral high-tech carbon fiber door that opens outward to maintain the unit's watertight integrity during installation or removal. The release of the module is simply accomplished by closing both doors and flooding the space between. The central corridor is permanently fixed to the structural base on the sea floor. On the other hand each unit is "neutrally buoyant".

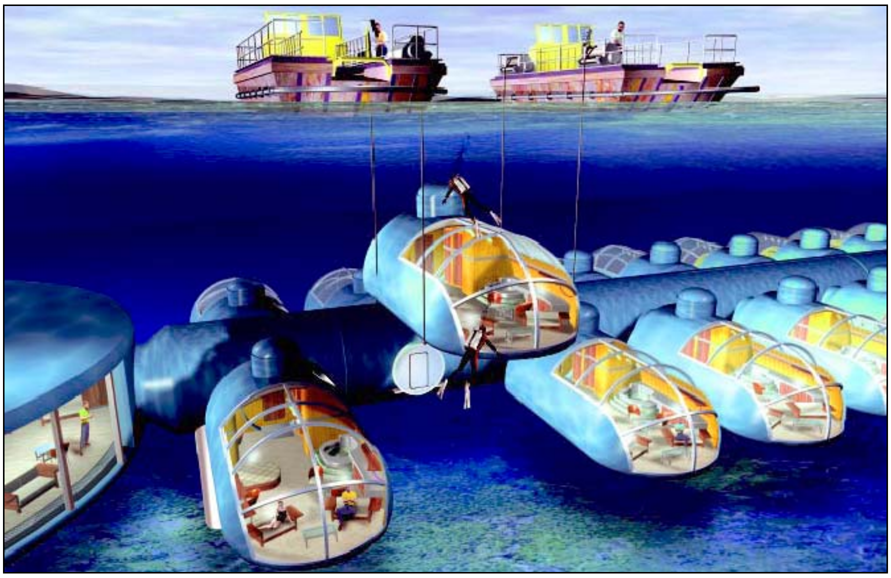

Figure 34. Placement of the suit modules.

L. B. Jones, "Re: Thesis-Poseidon Underwater Resorts," 1 November 2006, personal e-mail (3 November 2006).

5.2.2 Otter Inn [18]

The other example for hotel was *Otter Inn* that started to operate in 2000. It was designed and built by an artist *Mikael Genberg* in Sweden (Figure 35). The "one-room hotel" has two parts, over and below the waterline, were linked by a staircase. Above the waterline there is a raft with a typical Swedish wooden cabin. That cabin houses bathroom and kitchen whereas sleeping facilities are in the underwater part. The electricity supply is solar powered and air was supplied to underwater part by pipes which can be seen from Figure 36 below.

This example demonstrates the possibility of construction of underwater structures with simple and available technology and materials despite of its limitations and disadvantages. The idea of unusual accommodation that project offered is another purpose to evaluate this example.

[18] Data about the project was cited from: Burchard and Flesche, *Water House*, 120-121.

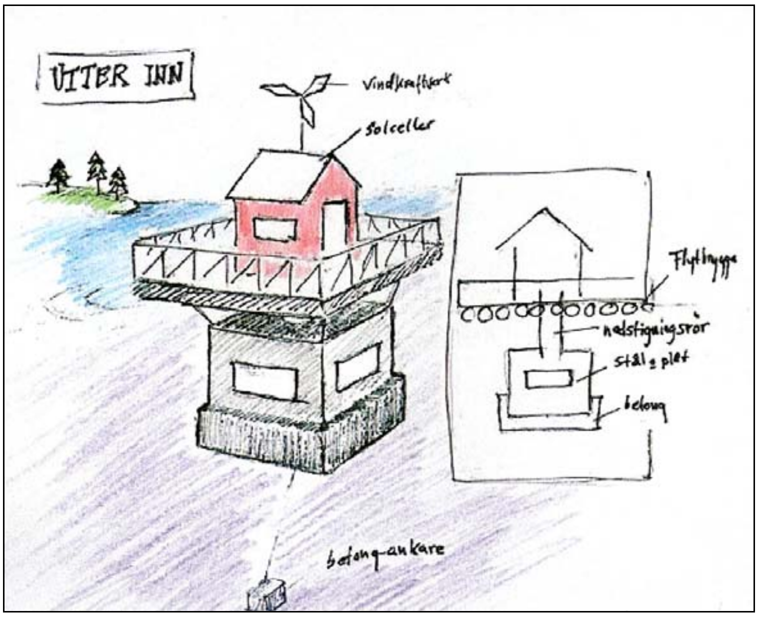

Figure 35. Concept drawing of one-room hotel by designer.

C. Burchard and F. Flesche, *Water House*, ed. F. Flesche (Munich: Prestel Verlag, 2005), 120.

i. Form and Geometry

Below water level, a watertight steel tank was constructed that was held by two anchors. Figure 36 demonstrates the whole structure. The 13 m² underwater is used as a bedroom.

ii. Degree of Enclosure

There are view ports on four sides of the structure to offer views of underwater world as shown in Figure 36.

iii. Entrance Space and Access

The part over the waterline also serves as an entrance and reception area. People can reach there by boats. Afterward the access to the submerged part is achieved by a stairway.

Figure 36. The whole structure.

C. Burchard and F. Flesche, *Water House*, ed. F. Flesche (Munich: Prestel Verlag, 2005), 121.

5.2.3 Ithaa Undersea Restaurant [19]

Ithaa- The Hilton Maldives Undersea Restaurant was opened on 15 April 2005 as a part of the *Hilton Maldives Resort & Spa*, sites in the Indian Ocean on Rangali Island. The structure sits **5 meters** beneath the water surface. It is surrounded by

[19] Data about the project was cited from:

Hilton Worldwide Resorts, "The Story of the First Aquarium-Style Undersea Restaurant in the World," http://www.hospitalitynet.org/file/152001986.pdf. (Last accessed in January 2007).

M. J. Murphy Ltd., "Undersea Restaurants," http://www.mjmurphy.co.nz/Projects/UnderwaterRestaurants/tabid/300/Default.aspx. (Last accessed in June 2007).

coral reefs and offers panoramic underwater views (Figure 37). The restaurant was built by *M. J. Murphy Ltd.* using technology which is common in public aquariums.[20]

Figure 37. Interior view of the restaurant.

M. J. Murphy Ltd., "Undersea Restaurants," http://www.mjmurphy.co.nz/Projects/UnderwaterRestaurants/tabid/300/Default.aspx. (Last accessed in June 2007).

i. Form and Geometry

The whole structure is 9 m x 5 m which was formed from three acrylic surfaces and two steel arches. As explained for submarines, steel arches stiffened the structure. Each surface has 5 m width and 3 m length from acrylic in 125mm thick. The acrylic surfaces were sealed to each other and the steel structure with a special underwater silicone sealant and the steel structure is protected by a special high quality marine paint system and a series of zinc anodes. The structure is supported on four 750mm

[20] Public aquariums are facilities which let visitors to experience the marine life under the ocean by means of many ways. Among them **acrylic tunnel** is one that make available to see marine animals and flora closely from behind an acrylic plastic while passing through them.

diameter steel piles (concrete filled), which were driven into the seabed. This method was selected to minimize the damage to the already existing reef.

ii. Degree of Enclosure

The idea, material and construction technique of transparent tunnels in public aquarium was used in the design of this undersea restaurant. There are many applications of acrylic tunnels around the world in various lengths and thickness according to the requirements. For instance, Figure 38 illustrates the different "profiles of acrylic tunnel" offered by the designer of *Ithaa* in aquarium applications.

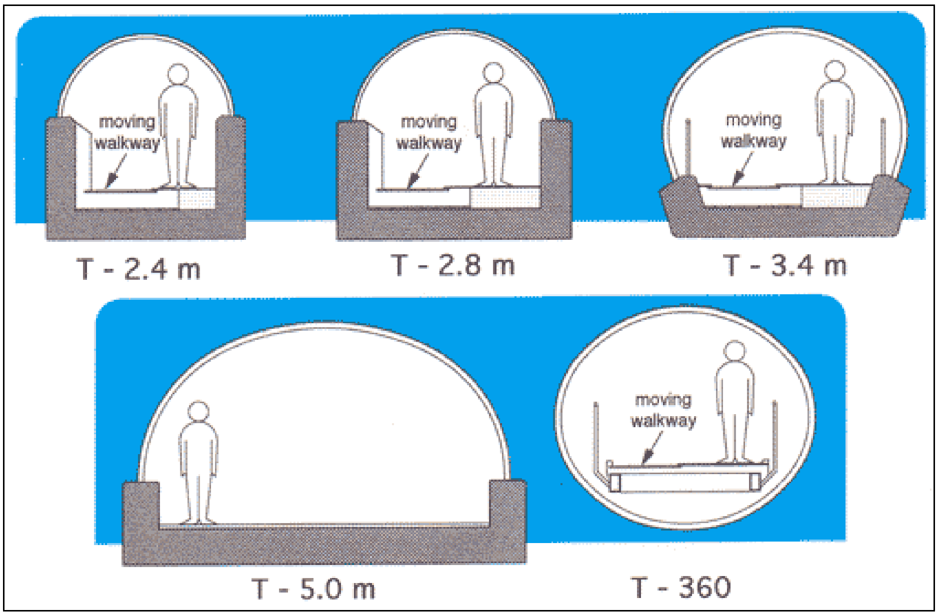

Figure 38. Acrylic tunnels profiles.

M. J. Murphy Ltd., "Acrylic Tunnel," http://www.mjmurphy.co.nz/ProductsServices/AcrylicTunnels/tabid/304/Default.aspx. (Last accessed in June 2007.

For this project, "T-5.0 m" type was utilized. As a result, 270-degrees panoramic underwater view was offered which can be interpreted as a proper approach for underwater design (Figure 39).

Figure 39. All transparent structure provides 270-degrees underwater view.

M. J. Murphy Ltd., "Undersea Restaurants," http://www.mjmurphy.co.nz/Projects/UnderwaterRestaurants/tabid/300/Default.aspx. (Last accessed in June 2007).

iii. Entrance Space and Access

Wooden jetty connect the entrance of the restaurant to the shore. Then, underwater structure can be accessed via a spiral staircase. Figure 40 displays the entrance part and the staircase during the process of being winched down into the water on rails.

iv. Construction and Assembling

The structure was built in Singapore and shipped to the island. Structure lowered in to the water over the piles (Figure 40). The weight of the structure was 175 tons and 85 tons of sand has been placed inside the structure to sink it into the sea. Afterwards, concrete was poured into the piles to lock the structure down securely to the plies.

Figure 40. Placement of the structure.

M. J. Murphy Ltd., “Undersea Restaurants,” http://www.mjmurphy.co.nz/Projects/UnderwaterRestaurants/tabid/300/Default.aspx. (Last accessed in June 2007).

5.2.4 Red Sea Star Underwater Restaurant [21]

The structure sits submerged **20 feet (6.10 m)** under water off the coast of Eilat in Israel (Figure 41). The design and construction of steel tank was developed by architect *Josef Kiriaty.* Interior designer*, Ayala Serfaty,* turned this space into a restaurant, inspired from aquatic world. The use of color balance the bluish aquatic light as explained in detail earlier. The architectural concept of the project consists of two sections which are above and below the sea. Upper part houses lounge, coffee bar and kitchen while dining area and bar located underwater.

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[21] Data about the project was cited from:

E. Cohen, “Under the Sea,” *Interior Design* 70, no. 9 (1999): 142. . Jul 1999; 70,9; Academic Research Library, pp(142-147). p. 142.

Burchard and Flesche *Water House*, 110-111.

Spiritual Architecture, “Red Sea Star,” http://www.spiritualarchitect.com/id3.html. (Last accessed January 2007).

Figure 41. Red Sea Star Restaurant exterior view under the sea.

Spiritual Architecture, “Red Sea Star,” http://www.spiritualarchitect.com/id3.html. (Last accessed January 2007).

i. Form and Geometry

The lower body was a steel tank which was built in a shape of a cross, that is, a combination of pentagonal alcoves as shown in Figure 42 and Figure 45. The form of the structure allows underwater view through windows to each seat (Figure 43).

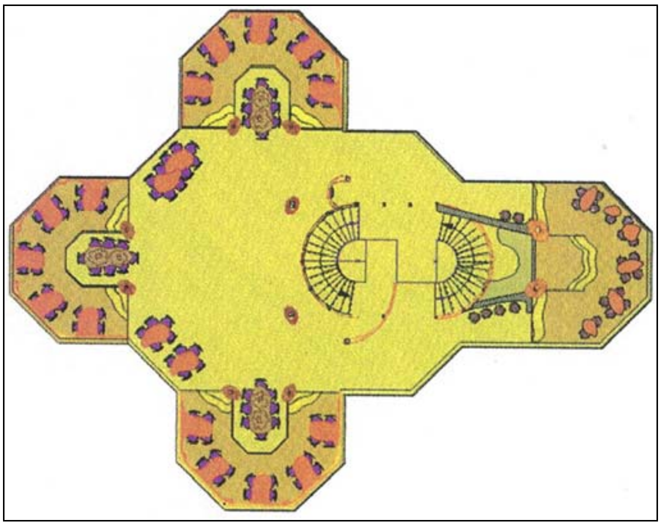


Figure 42. Plan of the Red Sea Star Restaurant.

Spiritual Architecture, “Red Sea Star,” http://www.spiritualarchitect.com/id3.html. (Last accessed January 2007).

ii. Degree of Enclosure

Underwater views were provided by 62 acrylic windows on steel walls and ceiling. Framed views (Figure 43) were achieved by this view ports as in the case of *Otter Inn hotel*.

Figure 43. Framed views to environment.

C. Burchard and F. Flesche, *Water House*, ed. F. Flesche (Munich: Prestel Verlag, 2005), 110-111.

iii. Entrance Space and Access

Visitors reach the entrance space of the restaurant above sea level by means of a bridge as illustrated in Figure 44. Then, diners descend two levels to the underwater part through the spiral staircase.

Figure 44. Restaurant is entered through a bridge and staircase.

Spiritual Architecture, "Red Sea Star," http://www.spiritualarchitect.com/id3.html. (Last accessed January 2007).

iv. Construction and Assembling

The underwater structure was constructed from steel plates which were welded together on land (Figure 45) and weighted down. Subsequently it was anchored by concrete to the sea bed.

Figure 45. The form and geometry of the undersea restaurant.

Spiritual Architecture, "Red Sea Star," http://www.spiritualarchitect.com/id3.html. (Last accessed January 2007).

5.3 Evaluation of Results of Study and Comments

For underwater structures the medium, itself totally limits and articulates the architecture. Since the structure is totally submerged the space should be completely closed. **Exterior spaces**, such as open and semi-open, can not be utilized under water. As a result**, fresh air** should be supplied from land with appropriate techniques and also direct **sun light** can not be utilized even on day according to depth. Along with technical solutions, interior design is important to provide spaces with high quality to occupants.

Before evaluating the comparison between contemporary examples, differences between contemporary examples and underwater habitats should be mentioned from architectural point of view since both of them were mainly proposed for people to survive their lives. Underwater habitats were mere shelters and comfort and space

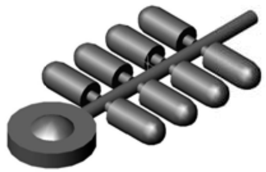
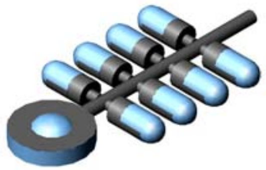
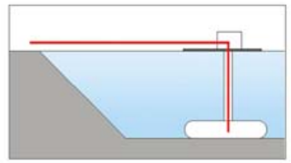
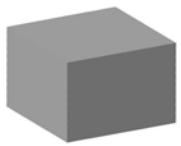
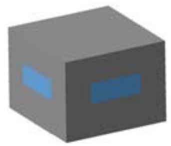
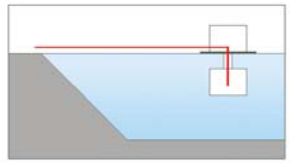
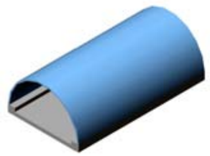
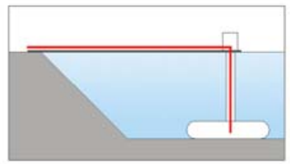
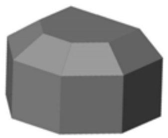
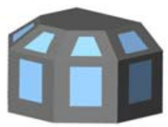
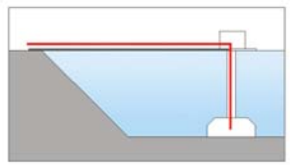
Project	Form & Geometry	Degree of Enclosure	Access
Poseidon Undersea Resort			
Otter Inn			
Ithaa Undersea Restaurant			
Red Sea Star Underwater Restaurant			

Figure46. Brief comparision of examples.

quality were not considered. Providing separate living, sleeping and bathroom quarters, cooking facility and systems for communication and television indicated the degree of comfort and habitability for these structures. Therefore underwater habitats can not be stated as architectural examples.

Figure 46 demonstrates the brief comparison of the contemporary examples in terms of form and geometry, degree of enclosure and access. As mentioned earlier, underwater design is an engineering standpoint and the main objective of the studies of engineers was to design structures which can resist to higher hydrostatic pressure in deeper. Although depth is not important for contemporary examples as for engineering projects; **form and geometry** of engineering structures were utilized in the examples of hotels and restaurants. In particular, *Poseidon Undersea Resort* consisted of various spaces with different dimensions since it proposed as a hotel. Therefore various forms combined according to the function it housed. For suits form of submarine was used whereas for public functions curvilinear walls with domes were used. *Ithaa Undersea Restaurant* utilized the technology of transparent acrylic tunnels and *Red Sea Star* Underwater Restaurant and *Otter Inn* were inspired from underwater tanks (Figure 46).

As mentioned previously designing in different environments have their own characteristics, limitations and differences. From this perspective, the basic and most significant matter is form and geometry, since the perception of interior space is related to form and geometry and it affects the other design parameters. Table 1 demonstrates the criteria that affect the form and geometry of structures in space, on land and under water. For the design of space colonies there are two important factors that limit the possible forms. Firstly, the habitat must contain an atmosphere in order to be habitable for human.[22] Secondly, residents must experience an acceleration to provide gravity and this can be accomplished by rotating the colony.

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[22] A. Globus and B. Yager, "Space Settlements: A Design Study," *National Aeronautics and Space Administration (NASA)*, http://www.nas.nasa.gov/About/Education/SpaceSettlement/75SummerStudy/Table_of_Contents1.html.

Thus, orbital colonies must be rotationally symmetric around at least one axis. This limits the practical shapes to the sphere, torus, dumbbell and cylinder. [23]

Table 1. Criteria for form and geometry of structures in different environments.

Environment	**Criteria for from and geometry**
Space	habitable atmosphere, rotation around axis
Land	gravity, wind, earthquake, live and dead loads
Underwater	hydrostatic pressure

Structures are facing wind force, effects of gravity, earthquake and dead and live loads on land. The pressure in the underwater structure should be equivalent to the pressure on land, one atmosphere. Therefore, structure should withstand the hydrostatic pressure greater than inner pressure. That limits the form and geometry of submerged structures.

Evaluation relating to **degree of enclosure** is very important for architectural approaches to underwater design. As noted before, maximizing transparency increases the relation between occupants and environment. This approach should be thought as one of the main objectives of underwater design.

The studies on submarines, transparent tunnels and the contemporary examples led to make an appraisal about the relationship between form and geometry; and the provided view to exterior. From this perspective, selected examples pointed out that transparency of underwater structure is directly related with its form and geometry. Namely, the selection of the form and geometry has an effect on the connection of

[23] A. Globus, "The Design and Visualization of a Space Biosphere," http://alglobus.net/NASAwork/papers/RNR-91-018/lewisOnePaper.pdf., 1.

occupants with the environment. Figure 47 illustrates the typology of surfaces and the results of the comparison of these examples can be listed as:

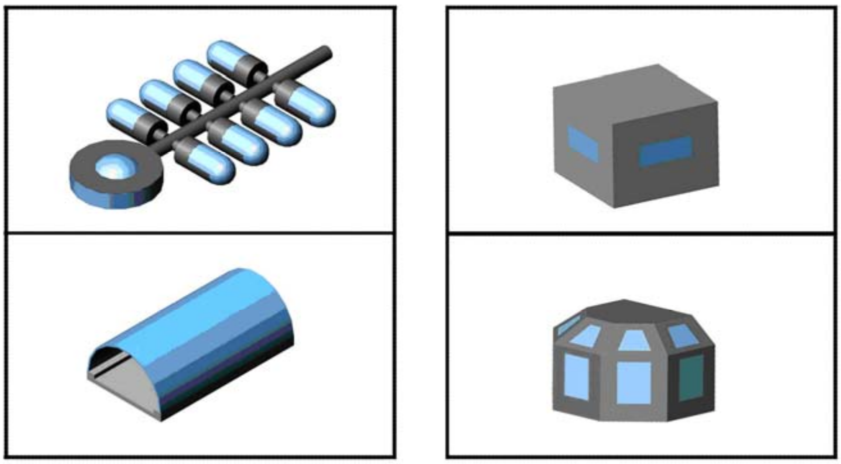

Figure 47. Typology of surfaces.

- Curvilinear surfaces, shells, can be completely transparent with appropriate material *(Poseidon Undersea Resort and Ithaa Undersea Restaurant)*.
- On the other hand for the non-curvilinear structures view ports were provided *(Otter Inn* and *Red Sea Star Underwater Restaurant)*.

View ports provided "framed views" to underwater, as in the case of aquariums. It is obvious that, this kind of manner is not appropriate to the nature of underwater design. As an alternative for transparent surfaces, a configuration for non-curvilinear structures with more view can be suggested as a steel box with semispherical windows as illustrated in Figure 48. An alternative for *Otter Inn*, lower part can be designed as a sphere to provide more views to underwater Figure 49.

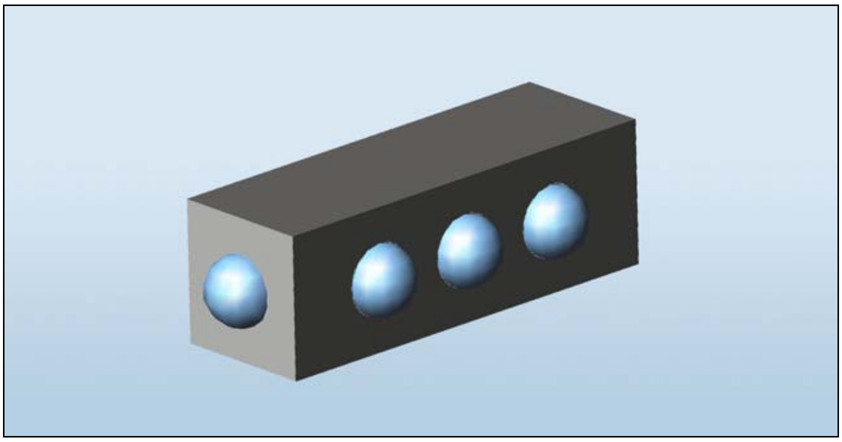

Figure 48. Box structure with semi spherical openings.

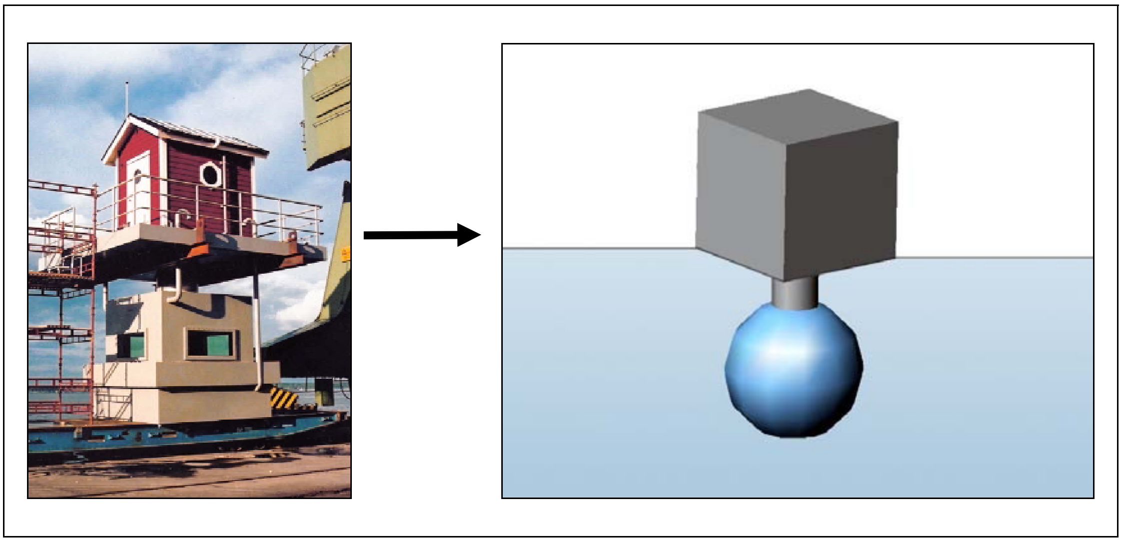

Figure 49. An alternative for Otter Inn.

In the mentioned examples **entrance** spaces were designed over water and **access** was provided from there through elevators or staircase in vertical tunnels (Figure 46). It can be affirmed as reasonable for structures that constitute the whole project. However especially for the projects that has buildings on land; access can also be proposed from these terrestrial parts as explained in detail and illustrated under section 5.1.4. Horizontal access tunnels can be proposed transparent to demonstrate the environment. In addition the type of the structure according to the function it houses, affects the design of entrance space and access. For example, the number of people coming to a restaurant at the same time will be greater than the number of people coming to a hotel at the same time. Therefore architectural approaches to the access tunnel and entrance space, such as dimension and characteristics of space, should be different and proposed accordingly.

In mentioned examples, **materials** which have been used in marine constructions were used. Steel and acrylic plastic were preferred for surfaces whereas concrete was used for anchoring and buoyancy. Transparency was achieved by acrylic plastic which had an extensive use in deep submersible and aquarium applications. New materials may be developed with collaborate study of architects with engineers by time to lead new opportunities which can meet the architectural approaches better.

Examples were also compared in terms of **required technology** in order to indicate their practicability. As mentioned earlier using curvilinear forms over the cubic ones is advantageous in terms of underwater view. On the other hand in terms of technology it has disadvantages since it require more advanced technology. When two examples which house same function compared, to construct a design like *Otter Inn* or *Red Sea Star Underwater Restaurant* is more easy since the technology of manufacture of steel tanks can be utilized. On the other hand for a design like *Poseidon Undersea Resort* or *Ithaa Undersea Restaurant* that maximizes the underwater view require more advanced technology so more difficult to realize.

Modular system can be required to design large scale projects which are composed of many units. According to the functions and space requirements different forms will be brought together to form the structure. The advantages of utilizing modular system in underwater design can be listed as:

- Variations of the project in different sizes can be built by adding or subtracting units. That leads to rise in the number underwater structures.
- Construction of underwater structures in modules will be functional in terms of emergency and maintenance.
- During a crack and leakage, there is a possibility that the entire structure will be collapse. To prevent this each module can be isolated in case of emergency.

- Ease of repair can be achieved by modular system. It will provide the units to be detachable and capable of being removed from the complex when required as achieved in *Poseidon Undersea Resort.*

Table 2 illustrates the evaluation of examples according to the applicable parameters defined previously. For this evaluation, “+”symbol was used to indicate success whereas “-” symbol indicated unsuccessful approach for that example. Any comment was not made about parameters which were not applicable for that example.

Table 2. Evaluation of examples.

Architectural Design Parameters	**Poseidon Undersea Resort**	**Otter Inn**	**Ithaa Undersea Restaurant**	**Red Sea Star Underwater Restaurant**
Degree of Enclosure	+	-	+	-
Relation with Entrance Space	+	+	-	+
Autonomy		+		
Safety	+			
Lighting	+		+	+
Use of Color				+
Modular Construction	+	-	-	-
Requirement of Advanced Technology	+	-	+	-

As shown in table, the results of the evaluation of study on contemporary examples can be listed as:

1. *Poseidon Underwater Resort* and *Ithaa Undersea Restaurant* were successful since they provide maximum view with transparent elements. Framed views were offered by *Otter Inn* and *Red Sea Star Underwater Restaurant* which was found as an inappropriate approach to underwater design.

2. For *Poseidon Underwater Resort, Otter Inn* and *Red Sea Star Underwater Restaurant,* functions were provided in the entrance space and linked with the space housed by submerged structure. That provides integrity between over and lower part of the project. On the other hand *Ithaa Undersea Restaurant* was unsuccessful from this perspective since only entrance was provided over water and linked by a staircase. There should be additional functions above and staircase links two functions to each other. Therefore, as long as the entrance space of submerged structure is provided over water level, functions should be housed in this space and linked functionally with the lower part.

3. Among the examples, dependency of structure is applicable for *Otter Inn.* This structure is autonomous in terms of electric energy since it supplies electric power from solar energy. For applications in the future, being wholly self-sufficient will provide continuity for large projects since hey have no relation with land. Besides, it may be an alternative for the energy resources.

4. In terms of safety *Poseidon Underwater Resort* was found successful since it safety dome and emergency entrance for each unit was proposed. In addition small submarines were suggested in critical areas. On the other hand, in other examples for safety of occupants the strength of the structure and material was designed accordingly. Architectural solutions should be thought together with rescue submarines and divers for these examples.

5. From the illustrative materials obtained, it was found that adequate lighting was provided to these examples to establish an appropriate living space.

6. *Red Sea Star Underwater Restaurant* was found successful in terms of use of color in interior design to deal with the effect of color of water. *Ithaa Undersea Restaurant* was wholly composed from transparent surfaces. For this example, the negative effect of color of water was not determined and it was explained with the depth of the seabed where structure was located.

7. *Poseidon Underwater Resort* was designed and constructed with modular system which can be stated as successful. Because modular system provide the construction of units on land and subsequently attach to each other or separate under water which lead to advantageous in safety and ease for repair.

8. For *Poseidon Underwater Resort* and *Ithaa Undersea Restaurant* advanced technology was required; in contrast for *Otter Inn* and *Red Sea Star Underwater Restaurant* simply technology for tanks is enough so it is easier to realize these structures. Being capable of using technology provides flexibility in design and lead to new alternatives for form and geometry and new space solutions. Therefore technology should be used in order to design spaces under water which are appropriate to this environment.

CHAPTER 6

CONCLUSION

Underwater has always been attractive for human beings. People have always struggled to employ and explore this world. In addition they even desired to live and work under water. There were many attempts which were performed by designers, scientists and inventors in history. While some of them had been realized; some had rested as ideas and proposals. However all of them pointed out the wish of human for being part of the underwater world. Myths and stories were written about submerged humans and vehicles operating under water. Oceans had been utilized firstly for exploration, fishing, military and mining industries. These were achieved by submarines and underwater habitats, which can be stated as merely engineering standpoint. Together with space, underwater was suggested as a new accommodation area to live in the future. Furthermore, the feasibility of underwater compared with space was emphasized.

As a result of curiosity, desire, challenge, and the developments in technology; underwater became a new medium for human to use for accommodation and entertainment with its unique characteristics and providing unusual experiences. Correspondingly, it is a new subject to study for architects. Although many proposals were achieved by architects so far, only few of them were able to be realized. In addition, recently underwater design became a race between designers and as a result underwater hotels and restaurants were proposed and constructed.

The study aimed to be a start point for further research and to guide architects for possible applications. This thesis intended to study the design considerations of underwater structures from both engineering and architectural aspects. In this study, first of all, the importance of underwater through history and the attempts which were carried out to utilize it in various manners were discussed. Secondly, the review of former underwater structures was presented to constitute a background for architects. In particular, brief information about submarines and underwater habitats was introduced. Afterwards, adequate knowledge about conditions and limitations of the environment and basic design considerations from engineering point of view was provided. Finally, architectural approaches to underwater design were discussed through contemporary examples. Environmental forces of the medium were noted and the differences from terrestrial structures were indicated. Architectural design parameters for underwater structures were defined and interpreted according to the environment. The applicable parameters were evaluated focusing on the contemporary examples with a comparative study. Under the light of this evaluation, comments and suggestions were made.

The results of the study on contemporary examples can be briefly stated as:

- *Poseidon Undersea Resort* and *Ithaa Undersea Restaurant* were found as successful in terms of being appropriate to the nature of underwater design from architectural point of view. In particular, for these examples the relations with exterior environment and convenient interior spaces were achieved successfully.

- *Otter Inn* and *Red Sea Star Underwater Restaurant* were successful structurally since being underwater was achieved; however from architectural point of view they were proposed as terrestrial buildings on land. Particularly, they should be designed more transparent to provide more visual relations

The major results drawn from this study can be summarized as follows:

- Each medium has its own rules and characteristics. From this perspective, underwater structures have differences from terrestrial ones.

- In particular, the main criterion which determines the form and geometry of underwater structures is hydrostatic pressure and it is totally different from the criteria for form and geometry of structures proposed on land and in space.

- Relations of building with site and surrounding are the criteria that affect form of terrestrial buildings. On the other hand, these factors are not considered for underwater structures. Together with hydrostatic pressure, interior space lay out creates form. In addition perception of the building from exterior is not important for underwater structures as for terrestrial ones. In contrast the structures can only be experienced from interior by occupants. Therefore form and geometry should be thought architecturally from this perspective.

- Along with hydrostatic pressure, water proof are the main problems which must be solved for underwater structures.

- Underwater is a totally new medium for architects and the environment itself limits and govern the architecture. Architects involving in this topic must support their imagination by appropriate technical knowledge and research. Even the conceptual architectural design phase should be supported by adequate knowledge about the environment and basic principles of underwater designing.

- The current underwater technology is capable to propose spaces under water which will provide appropriate quality and comfort to live to human as terrestrial ones.

- Although material, form and geometry and construction techniques of former structures can be utilized; the quality of space should be considered from architectural standpoint. Precisely, use of color and lighting, providing exterior view, character of entrance spaces and way of access and design of interior space should be thought and proposed by architects.

- For underwater structures the variety of space typology is limited and only interior spaces can be achieved. Therefore, design and lay out of interior space is important.

- One of the main objectives of architectural underwater design should be providing relation between human and environment. Therefore transparency is important for underwater structures. Utilizing transparent shell elements is a more appropriate approach instead of windows.

- Some of the designers of the mentioned underwater hotels and restaurants projects were engineers, because technology was required for these structures and it was provided from engineering applications. On the other hand, architects should study with engineers and benefit from their experiences to generate new alternatives. To illustrate, new functions can be located underwater and new spaces and forms may be required. These spaces and their qualities will be determined by architects. Later appropriate form and geometry combinations can be studied together with engineers.

- New understanding of hotel and restaurant design revives the tourism and economy of region and country. From this perspective, underwater hotels and restaurants probably play an important role. Since they offer different experiences many people want to stay or eat in these places. In addition, new areas are searched to make investments.

- Investors prefer structures that provide different experiences to their customers. Accordingly, submerged structures that house commercial facilities may be a highly profitable investment. The underwater view which will provide interesting and unusual experience leads to market differentiation for owners.

- Although the initial cost of an underwater structure may be higher than the terrestrial ones, differences which were provided by these structures lead to advantages and profit. For this reason, initial higher cost can be paid for short time periods. People may prefer to eat in an underwater restaurant for just the unusual experience.

- Possible applications for Türkiye should be taken into consideration because of its geographical location, namely three sides of the country is covered with seas.

Underwater structures near the shores, which provide differentiation, will make affects positively the tourism and economy of the country. Native and foreign tourists will prefer to stay an underwater hotel or eat in an undersea restaurant and prefer Türkiye for these structures.

- Instead of foreign companies, firstly architects can study with Turkish engineers who were experienced in hydrostatic and submarines in design phase. Later, local companies may be established to improve this field of construction and increase the number of these structures.

- Design of an ideal underwater structure is a specific research matter. Therefore, each aspect studied in chapter 5 can be studied in detail in further studies. In addition the structural capacity and behavior of the new geometrical configurations should be analyzed with considering other properties.

REFERENCES

Ambrose, J. E. *Building structures primer.* New York: Wiley, 1967.

Burchard, C. and F. Flesche. *Water House*. Edited by F. Flesche. Munich: Prestel Verlag, 2005.

Burcher, R. and L. J. Rydill. *Concepts in Submarine Design.* London: Cambridge University Press, 1995. http://books.google.com/books?hl=en&lr=&id=cN4cdjU5KTcC&oi=fnd&pg=RA2-PR11&dq=+%22Concepts+in+Submarine+Design%22+Burcher&ots=8kK90IIz4H&sig=Nek0lkI2cDG5nj3CDXrmopsg84w. Last accessed in May 2007.

Ching F. D. K. *Architecture: Form, Space, & Order*. 2nd ed. United States of America: John Wiley & Sons, Inc., 1996.

Ching, F. D. K and C. Adams. *Building Construction Illustrated*. 2nd ed. New York: Van Nostrand Reinhold, 1991.

Cohen, E. "Under the Sea." *Interior Design* 70, no. 9 (1999): 142-147.

Dreiseitl, H., D. Grau and K. H. C. Ludwig**.** *Waterscapes: Planning, Building and Designing with Water.* Germany: Birkhauser, 2001.

Frangopol, D. M. and S. Recek. "Reliability of fiber-reinforced composite laminate plates." *Probabilistic Engineering Mechanics* 18, (Elsevier Ltd., 2003): 119-137.

George, F. B. Foreword. In *Living and Working in the Sea,* 2nd ed., *by* J. M. Miller and I. G. Koblick, xi-xii. Plymouth: Five Corners Publications, Ltd., 1995.

Globus, A. "The Design and Visualization of a Space Biosphere." http://alglobus.net/NASAwork/papers/RNR-91-018/lewisOnePaper.pdf. Last accessed in February 2007.

Globus, A. and B. Yager. "Space Settlements: A Design Study." *National Aeronautics and Space Administration (NASA).* http://www.nas.nasa.gov/About/Education/SpaceSettlement/75SummerStudy/Table_of_Contents1.html. Last accessed in February 2007.

Go, J. "Buckling Arch under Normal Pressure." Ph. D. Thesis, Michigan State University, 2004.

Hernandez, F.A. "Underwater Farming Colonies: A new Space for Human Habitation." Master's Thesis, University of Southern California, 2002.

Hilton Worldwide Resorts. "The Story of the First Aquarium-Style Undersea Restaurant in the World." http://www.hospitalitynet.org/file/152001986.pdf. Last accessed in January 2007.

Jones, L. B. "Re: Thesis-Poseidon Underwater Resorts." 1 November 2006. Personal e-mail (3 November 2006).

Kaji-O'Grady, S. and P. Raisbeck. "Prototype cities in the sea." *The Journal of Architecture* 10, no. 4 (2005): 443-461.

Kubba, S. *Space Planning for Commercial and Residential Interiors.* United States of America: McGraw-Hill, 2003.

Lai, W. H. "Transient dynamic response of submerged sphere shell with an opening subjected to underwater explosion." *Ocean Engineering* 34, no. 5-6 (Elsevier Ltd., 2007):653-664.

Liang, C., H. Chen and C. Jen. "Optimum design of filament-wound multilayer-sandwich submersible pressure hulls." *Ocean Engineering* 30, (Elsevier Science Ltd., 2003): 1941-1967.

Liang, C., W. Lai and C. Hsu. "Study of nonlinear responses of a submersible pressure hull." *Pressure Vessels and Piping* 75, (Elsevier Science Ltd., 1998): 131-149.

Liang, C., T. Teng and W. Lai. "A study of diving depth on deep-diving submersible vehicle." *International Journal of Pressure Vessels and Piping* 75, no.6 (Elsevier Science Ltd., 1998): 447-457.

M. J. Murphy Ltd. "Undersea Restaurants." http://www.mjmurphy.co.nz/Projects/UnderwaterRestaurants/tabid/300/Default.aspx. Last accessed in June 2007.

M. J. Murphy Ltd. "Acrylic Tunnel." http://www.mjmurphy.co.nz/ProductsServices/AcrylicTunnels/tabid/304/Default.aspx. Last accessed in June 2007.

Miller, J. M. and I. G. Koblick. *Living and Working in the Sea,* 2nd ed. Plymouth: Five Corners Publications, Ltd., 1995.

Miller, S. "How an underwater habitat benefits marine-science." *National Oceanic & Atmospheric Administration.* http://www.uncw.edu/aquarius/about/sciamart.htm. Last accessed in April 2007.

Moon, H.Y. and K. J. Shin. "Evaluation on steel bar corrosion embedded in antiwashout underwater concrete containing mineral admixtures." *Cement Concrete Research* 36, (Elsevier Ltd., 2006): 521-529.

Moore, C. W. and J. Lidz. *Water+Architecture.* Japan: Thames and Hudson Ltd., 1994.

Mouritz, A. P., E. Gellert, P. Burchill and K. Challis. “Review of advanced composite structures for naval ships and submarines.” *Composite Structures* 53, (Elsevier Science Ltd., 2001): 21-42.

Munson, B. R., D. F. Young and T. H. Okiishi. *Fundaments of Fluid Mechanics.* New York: John Willey & Sons, 2002.

Onouye, B. *Statics and strength of materials for architecture and building construction.* Upper Saddle River, NJ: Prentice Hall, 2002.

Özden, H. and K. T. Gürsel. “Çok Amaçlı Kullanımlı Yarı-Batık Yüzer Ada Tesislerinin Tasarımı.” *Gemi Mühendisliği ve Sanayimiz Sempozyumu*, (2004): 386-396. http://www.gidb.itu.edu.tr/staff/unsan/Kongre2004/41.pdf. Last accessed in June 2007.

Ross, C. T. F. “A conceptual design of an underwater vehicle.” *Ocean Engineering* 33, (Elsevier Ltd., 2005): 2087-2104.

Ross, C. T. F. “Design of Submarine.” *University of Portsmouth*. http://www.mech.port.ac.uk/CTFR/concept/sub_1.pdf. Last accessed in February 2007.

Ross, C. T. F. “Design of Submarine.” *University of Portsmouth*. http://www.mech.port.ac.uk/CTFR/concept/sub_2.pdf. Last accessed in February 2007.

Ross, C. T. F. “Design of Submarine.” *University of Portsmouth*. http://www.mech.port.ac.uk/CTFR/concept/sub_4.pdf**.** Last accessed in February 2007.

Ross, C. T. F. “Design of Submarine.” *University of Portsmouth*. http://www.mech.port.ac.uk/CTFR/concept/sub_5.pdf. Last accessed in February 2007.

Salvadori, M. G. *Structure in architecture.* New Jersey: Prentice-Hall Inc., 1963.

Sezen, A. *The Underwater Hotel: Construction-Structure-Design.* Ankara: Öncü Basımevi, 2004.

Straw,J. L. “Re: Master’s Thesis-Jules’ Underwater Hotel.” 9 November 2006. Personal e-mail (10 November 2006).

Spiritual Architecture, “Red Sea Star,” http://www.spiritualarchitect.com/id3.html. Last accessed January 2007.

U.S. Submarines Inc., “Habitats Sea Floor Concept,” http://www.ussubs.com/habitats/floor_concept.php3. Last accessed in April 2007.

U.S. Submarines Inc., “Habitats Sea Room Activity Center,” http://www.ussubs.com/habitats/activity_center.php3. Last accessed in April 2007.

U.S. Submarines Inc., “Habitats Superior One Atmosphere,” http://www.ussubs.com/habitats/atmosphere_habitat.php3. Last accessed in April 2007.

Unwin, S. *Analysing Architecture.* 2nd ed. New York: Routledge, 2003.

Watson, T. “Sleep with the fishes.” *Canadian Business* 77*, no. 3 (2004): pN.PAG.* http://web.ebscohost.com/ehost/detail?vid=2&hid=12&sid=e8710853-c2cd-4593-9a59-c1146879a751%40sessionmgr3. Last accessed in May 2007.

Ward, C. “One Fish, Two Fish, Red Fish, Blue Fish: A Journey into the Oceans.” Master’s Thesis, Dalhousie University, 1998.

Yanmaz, A. M. *Applied Water Resources Engineering.* An*kara:* Metu Press, 1997.

“Chapter 10: Submarines and Submersibles,” *US Naval Academy*. http://www.usna.edu/naoe/courses/en200/ch10.pdf, 10. Last accessed in January 2007.

*“*Physics of Liquids & Gases.*”* http://www.vectorsite.net/tpecp_08.html. Last accessed in January.

“Shell Structures: Basic Concepts,” http://www.colorado.edu/engineering/CAS/courses.d/AFEM.d/AFEM.Ch29.d/AFEM.Ch29.pdf, 29-3. Last accessed in April 2007.

“Submarine History.” http://www.globalsecurity.org/military/systems/ship/sub-history.htm. Last accessed in January 2007.