Durability with regards to concrete was defined by the American Concrete Institute's (ACI) committee 201 in 1962 to be "resistance to deteriorating influences which may through inadvertence or ignorance reside in the concrete itself, or which are inherent in the environment to which it is exposed."(Woods, 1968) Reinforced concrete is considered to be a very durable building material. In general, designers in the United States do not have to worry about taking extra steps to design for durability if their structures meet requirements outlined in building codes. In fact, most well designed structures will have no durability issues during their lifetimes. In fact, some concrete structures such as Pantheon in Rome still exist from the ancient era. However, occasionally there are circumstances in which extreme environments or special circumstances require thinking about, considering, and designing for the durability of reinforced concrete structures.

This paper will discuss four topics regarding the durability of reinforced concrete. The first section will discuss three common causes of durability issues in reinforced concrete: rebar corrosion, sulfate attack, and concrete cracking. The second section of this paper will outline ACI code provisions which set durability requirements. Following this the paper will explore measures that can be taken to improve the durability of structures that are to be built in extreme environments. Finally, this paper will briefly discuss durability based design, a new method being proposed to help designers achieve better durability results for their structures.

As stated previously three common causes of durability issues in reinforced concrete structures are rebar corrosion, sulfate attack, and concrete cracking. Rebar corrosion can prove to be a serious problem in reinforced concrete structures. Rebar corrosion exists as a problem due to the chemical composition of steel. Steel is an alloy consisting mostly of iron. When in contact with electrolytes (a common electrolyte is impure water) the iron in steel will tend to return to a state in which it is more commonly found in nature, iron oxide. Iron oxide is more commonly known as rust, a fragile and brittle compound not suitable for use as reinforcement.

In order for the steel to oxidize it requires the presence of an electrolyte. Since steel is encased in concrete it is usually protected from electrolytes and therefore does not rust. Furthermore, the alkalinity of the concrete helps to protect the steel by oxidizing the outer layer of the steel. This thin oxidized layer protects the steel encased inside it from corrosion by acting as a protective shield against oxidation of the interior.

When deterioration of the rebar, or of the concrete itself, occurs it generally happens in two stages. First, a fluid containing a reactant will penetrate the member. Then, when that fluid comes in contact with a reactant a reaction occurs, resulting in corrosion or deterioration of the reactant. With regards to steel specifically, what happens is impure water penetrates into the concrete. The water may contain chlorides such as salts which increase the conductivity of the water, but this isn't required for corrosion. In the presence of water an electric current flows through the steel and water. This electric current causes oxygen in the water or present in the concrete to react with the steel.

There are two issues when rebar corrosion occurs in reinforced concrete structures. First, oxidized steel is not as strong as pure steel. This has the consequence of reducing the strength of the affected structure and can also result in increased deflections. A second consequence of corroded steel is due to the expansion of the steel due to rusting. Corroded steel takes up a larger amount of space than pure steel. This can lead to possible cracking and spalling of the concrete encasing the steel. The negative effects of concrete cracking will be discussed shortly.

Sulfate attack is sometimes an issue in concrete structures. Sulfates can be inherently present in concrete or can come from external sources. Three results can occur when sulfates interact with concrete: eating away of the cement, expansion and cracking of the member, and scaling. Sodium sulfate, one common sulfate compound, produces two of these results when it reacts with concrete. Sodium sulfate reacts with the cement paste to produce ettringite, a product which is larger in volume than the reactants from which it was formed. This can result in expansion and cracking of the concrete due to the larger volume of the ettringite. Furthermore, the reaction removes cement from the concrete, resulting in less strength. Magnesium sulfate, another common sulfate compound, does not produce expansive products when it reacts with cement paste like sodium sulfate. The products the reaction creates, however, bond in a weaker fashion than the bond created by pure cement paste. Scaling can occur when either type of sulfate is present. Scaling occurs when fly ash is present in concrete attacked by sulfates, though this result is quite rare.

A durability issue similar to sulfate attack is the presence of reactive aggregates in the concrete. Occasionally aggregates are used that react with the alkali in the concrete. One of the common results of this reaction is a product that is larger than the reactants which, like ettringite in the sulfate reaction, results in cracking of the concrete.

Concrete cracking has many causes. Two of the possible causes have already been discussed: sulfate attack and rebar corrosion. Other possible causes are improper curing, impact loads, extreme loadings during construction, and flexural stress induced in moving precast concrete members. Another very common cause of concrete cracking is the freeze-thaw cycle, where water seeps into the concrete through small cracks and expands when the water freezes. This expansion causes more cracking to occur; allowing more water to protrude into the concrete and allowing the freeze-thaw problem worsen in a cyclical fashion. Freeze-thaw damage does not usually occur due to water that is trapped in the concrete during placement and curing; this trapped water is generally under a large enough amount of pressure that it cannot freeze. Concrete must therefore be wetted externally before freeze-thaw damage can occur. Deicing agents can lead to a type of freeze-thaw damage as well by melting ice that has formed on the surface of the concrete, which creates liquid water that can seep into the concrete, refreeze, and cause cracking near the surface of the concrete (which is called scaling).

Concrete cracking has a few adverse effects. Cracking can expose rebar which makes the rebar more vulnerable to corrosion. This can then lead to more cracking. Cracked concrete will also deflect more due to a smaller section modulus. Affected members will also have less strength than members which are intact. Cracking is also unsightly and could lead to safety concerns among tenets, owners, and building inspectors.

The ACI code has a section on durability which sets requirements to limit the effects of the three common durability issues discussed above. One of the ways that the code deals with durability is to set a combination of maximum water-cement ratio and minimum compressive strength. This type of requirement exists for freeze-thaw conditions and for environments containing sulfates. Research has shown that increasing the percentage of cement decreases damage from these two attacks. Furthermore, the minimum strength requirement is set to ensure that the minimum water-cement ratio is met. Freeze-thaw and sulfate conditions both have other requirements as well. The code requires that structures in freeze-thaw conditions have a certain amount of entrained air. Entrained air is added to concrete through the use of an admixture, and it limits damage by creating air pockets in the concrete that give space for freeze-thaw cycles to occur without damaging the concrete. An experiment was conducted by the Portland Cement

Association over an extended period of time on concrete cubes with and without entrained air. The cubes with entrained air suffered little damage while those without were severely damaged and unsuitable for use (Woods, 1968). The code also specifies the maximum amount of cement replacement materials that can be used in the mix; these additives, such as fly ash and slag, are limited as concrete made with these elements do not fare as well under freeze-thaw conditions as concretes without.

Sulfate environments have two additional requirements in addition to the water-cement ratio and compressive strength. The first of these is a requirement for the use of certain cement types which are resistant to sulfate attack. These cements are also specified to have a limited amount of C3A, tricalcium aluminate, which reacts with sulfates. The code also requires that calcium chloride not be used in extreme sulfate environments to limit rebar corrosion.

Requirements to protect the rebar from corrosion are also set in the code. The primary goal of the rebar protection requirements in the durability section of the code is to protect the rebar from chlorides. The code sets limits on the maximum amount of chloride ions that can be present in the concrete. Furthermore, the code sets requirements on maximum water-cement ratio and minimum compressive strength in the event the concrete is exposed to sea water, deicing agents, and salts. The goal of these two requirements is to limit damage to the concrete; damage which could expose the rebar in these environments.

Other durability requirements in the ACI code exist outside of the durability section. Minimum cover is set in various places in the code to ensure a layer of protection for the steel. Minimum steel requirements are set to protect members from cracking due to creep and shrinkage. Some durability concerns are not covered in the code, however. The commentary in the durability section of the code states that the code does not cover extreme conditions which could cause durability concerns with the structure. These conditions do occasionally occur.

Oceanic environments are one of extreme environments not explicitly covered in the ACI code. Structures built in these environments can range from wharfs to bridges. In addition to being used as structural elements in these situations, reinforced concrete can be used to protect steel members from corrosion. Reinforced concrete members in oceanic environments will have three types of contact with water: they will be completely submerged, they will have regular contact with water, or they will be irregularly sprayed with water. Submerged reinforced concrete generally has few problems. The fact that it is submerged means that little oxygen exists, making corrosion nearly impossible. The steady presence of water also means that erosion of the concrete is less of an issue. While reinforced concrete right at the water-air interface can have some abrasion problems, this area also has few problems. This is because it is usually saturated with water, limiting oxygen contact. The area above this, where spray from the ocean only occasionally reaches the concrete can have severe issues due to the area not being saturated with water.

There are three effects of ocean spray. Ocean water carries salts, dissolved oxygen, and dissolved carbon dioxide. Carbon dioxide lowers the alkalinity of concrete, which can decrease the passivity of the rebar inside. Salts increase the likelihood of steel corrosion by increasing the conductivity of liquids (i.e. water) that may reach the steel. Oxygen reacts with steel in the presence of an electrolyte. Oxygen can also lead to differences in electric potential inside a rebar. This difference in electric potential can induce an electric current which in turn can induce extra corrosion in the steel.

Issues with durability in oceanic environments reach beyond the physical nature of the ocean though. Few design procedures exist for structures in these areas, causing problems for designers attempting to establish a suitable design. Constructability can also be an issue. Cover can be less than optimal due to the difficulty of placing concrete in such environments. It is also difficult to generate performance specifications for contractors due to the limited link between lab data and durability performance. This lack of correlation can lead to underperforming structures that require repairs shortly after construction.

There are a number of solutions that have been used or suggested to prevent the deterioration of reinforced concrete structures in oceanic environments. In Ashdod, Israel fiber reinforced concrete "aprons" were used to protect steel piles at a port facility instead of traditional reinforced concrete aprons. After four years these fiber reinforced aprons exhibited little damage, in contrast to the multitude of problems the port saw previously from the traditional aprons (Chernov, Zlotnikov, Shandalov, 2006). Fiber reinforced concrete works well for this type of application because the fibers limit cracking and also have less continuity. This lack of continuity makes the steel less prone to corrosion by separating the individual steel elements. Synthetic fibers could also be used, eliminating the possibility of corrosion all together. Another more traditional method that has been suggested is to use concrete with a low water-cement ratio and with silica fume. This would result in a concrete that is extremely dense and has little porosity, limiting the penetration of salt water. Epoxy coating for the rebar is also an option, though one has to be careful as even a small hole in the coating can expose the entire bar to corrosion. Coatings for rebar also can result in a weaker bond between the steel and the concrete, so this must also be taken into account if a designer chooses to use coatings to protect rebar. There are also additives that can be mixed into the concrete such as sodium nitrate which react with chlorides, thereby protecting rebar from corrosion. Hubert Woods (1968) reminds us though that concrete additives and rebar coatings should only be used as backup options only, and that "design provides the first line of defense."

Conventional design procedures take some steps to limit cracking. In some cases, however, there is a need for a very minimal amount of cracking. A case where this is very important is in tunnels. Cracks in tunnels would allow for water and other materials to enter into the tunnel. Cracking could also endanger the structural integrity of the tunnel. Some precast concrete elements which are subjected to highly abrasive forces or cracking during unmolding could also benefit from the same procedures used to limit cracking in tunnels.

One of the most effective ways shown to limit cracking is to use fiber reinforcement in the concrete. A tunnel in Barcelona, Spain used steel fibers to protect against cracking in addition to using tradition reinforcement for strength requirements. This method proved very successful in limiting cracking for the designers (Gettu, Barragán, Garcia, Ortiz, Justa, 2006). Another possibility is to use controlled permeability formwork when constructing structures which require little cracking. This formwork improves the quality of the cover of the member by keeping the water-cement ratio low in the exterior portions of the member. By improving the quality of the concrete cover, fewer cracks are likely to form in the cover zone, and therefore fewer cracks are likely to form in the entire member.

Reinforced concrete structures built in the Middle East are subject to a combination of environmental factors that are hostile to reinforced concrete. Structures built in the Middle East are exposed to ocean spray due to the region's proximity to salt water seas. This makes the structures vulnerable to rebar corrosion from salt as well as weathering of the concrete from both wind and sea spray. Sulfates are also present in high concentrations in the Middle East, making concrete deterioration a problem. The dry, hot conditions in the region also lead to cracking due to the drying of the concrete. Furthermore, reactive aggregates tend to be used occasionally in the region, leading to more reactivity problems.

The various problems caused by constructing reinforced concrete structures in the Middle East require a number of solutions to adapt to all of the problems. One of the more effective ways of improving durability in this region is to increase the amount of cover in members. Research has shown that a doubling of concrete cover leads to a quadrupling of service lifetime (Goring, 2005). Additional cover would provide an extra barrier against the chemical threats that are prevalent in the region. Other methods that provide additional protection against chemical attacks are the use of special paints to cover members in a protective layer and the placement of cladding on structures to protect the concrete members from outside attack. These methods have some drawbacks: painting can leave spots unpainted and exposed, the chipping away of paint can occur, enclosing members in cladding or painting them may not be architecturally sound, and providing cladding may not be possible at all locations in a structure.

Another way of protecting these structures could be to use fiber reinforcement (steel or synthetic). Strength or deflection issues may require that traditional reinforcing be used, but fibers could be used in addition to provide an additional layer of protection. As has been discussed previously, fibers can reduce the amount of cracking in a member. This would help protect the member against the ingress of damaging chloride ions and could also provide extra resistance against cracking from drying.

Using additives such as pozzolans and silica fume in the concrete mix has also been suggested as a way of reducing damage from sulfates, which are prevalent in the region. This, however, can have mixed results. Silica fume and pozzolans will only help prevent damage from certain sulfate compounds. Pozzolans, for example, reduce damage from sodium sulfates but actually increase damage from magnesium sulfates. A designer who specifies additives will have to consider the type of sulfate attack he or she expects if they choose to use additives to reduce/limit sulfate damage.

One of the innovations that has arisen out of the need for durable designs in the Middle East is the concept of durability based design. Currently very little is specified in building codes about performance criteria for durability. Codes will specify that certain steps must be taken in design to ensure a level of durability, but the codes do not specifically mention that a certain durability condition must be met. Durability based design attempts to set, or have designers set, a certain level of performance that their structures must meet.

Setting the goals for durability based design has been one of the challenges for proponents of the method. Traditionally durability performance has been linked to the compressive strength of concrete. However, research has shown that there is little correlation between durability and compressive strength (Hooster, Midness, Roumain, Boyd, Rear, 2006). Durability is directly related to the degradation of the concrete and steel. Researchers are currently attempting to model and quantify the rate of degradation of these principal components of reinforced concrete structures.

One example of how durability based design could be used in the future can be seen in a durability based design program currently used in the Persian Gulf region. DuraPGulf is a program used to model chloride attack on reinforced concrete members. The program works on the assumption that a reinforced concrete member's lifetime is equal to the amount of time it takes chloride ions to eliminate the protective coating surrounding the steel, which leaves the rebar prone to chemical reactions and degradation. The program takes in details about the member such as the amount of concrete cover, curing conditions, mixture proportions, and surface treatments to output a life time. With a desired lifetime in mind, a designer can then go back and modify the member until the desired lifetime is reached. The program is still fairly new and rudimentary, but it demonstrates how durability based design could work in the future.

Durability issues in reinforced concrete structures do occasionally occur. The ACI code sets requirements to protect structures against the more common issues such as rebar corrosion, sulfate attack, and concrete cracking. Sometimes, however, structures face more severe conditions which are not covered in the code. These conditions include locations such as marine environments, tunnels, the Middle East. These conditions require designers to adopt special designs to cope with the additional stress on their structures. The extremity of some of these conditions has lead engineers to think about using durability based design methods, where structures are designed with a set service lifetime in mind. Durability is an issue in reinforced concrete design, but a well prepared designer can find ways to adapt to the situation.