A Fuzzy Logic Material Selection Methodology for Renewable Ocean Energy Applications

by

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Abstract

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The purpose of this thesis is to develop a renewable ocean energy material selection methodology for use in FAU’s Ocean Energy Projects. A detailed and comprehensive literature review has been performed concerning all relevant material publications and forms the basis of the developed method. A database of candidate alloys has been organized and is used to perform case study material selections to validate the developed fuzzy logic approach. The ultimate goal of this thesis is to aid in the selection of materials that will ensure the successful performance of renewable ocean energy projects so that clean and renewable energy becomes a reality for all.

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1 Introduction and Objective

1.1 Introduction

In 1882, the French scientist Jacques d'Arsonval proposed that the solar energy stored in the warm tropical seas could be used to power a heat engine [1]. The ocean thermal energy conversion (OTEC) concept began to be seriously considered by the United States Department of Energy after the energy crisis of the 1970's. In this approach a working fluid, usually ammonia, is evaporated in a heat exchanger by warm surface water, drives a turbine to produce power, and then is condensed in another heat exchanger by cold deep ocean water. However, the efficiency of this OTEC process was low and efforts to develop it were diminishing by the late 1980's.

As the world's supply of fossil fuels gradually depletes and the price of energy continues to rise we once again turn to renewable ocean energy as a solution. The OTEC process and several other renewable energy systems are currently being researched and developed at Florida Atlantic University. One of the most promising energy conversion systems is the ocean kinetic energy conversion process (OKEC). OKEC capitalizes on the kinetic energy that exists in waves, currents and tides. This kinetic energy is converted to electrical energy by turbines or wave buoys. The OKEC system currently being developed at FAU employs a turbine mounted to a pressure vessel housing a generator. Due to its close proximity to the Gulf Stream Current FAU is in a perfect position to develop the technology to make ocean kinetic energy conversion a reality. FAU is helping to bridge the technological gap necessary to implement ocean current turbines in the Gulf Stream.

Florida lacks the consistent winds for reliable wind energy and lacks the consistently clear skies necessary to attain solar energy during peak energy consumption months. The ocean off the coast of south Florida can potentially provide a large enough source of energy to make large scale power production feasible year round. A virtually limitless source of kinetic energy, the Gulf Stream Current, flows eastward through the Florida Straits then heads northwards along the coast. The Gulf Stream current has a mass transport greater than thirty times that of all the freshwater rivers in the world combined. It has an average annual velocity of 1.56 m/s at its core. The water off the coast of Southern Florida is also a great location to set up OTEC processes. There is a sharp thermal gradient between the warm surface waters and the colder deep-sea water. The water near the surface has an average temperature of 27° C.

FAU is manufacturing a pilot renewable energy system and is preparing to test it in the Gulf Stream. The testing will determine overall feasibility, give an estimate of the power producing capabilities and uncover any design flaws or unforeseen reactions. The pilot project consists of a twin-pontoon platform and a scale OKEC model that will be lowered down from the platform. The twin-pontoon platform will be attached to a steel buoy moored to the ocean floor. Stainless steel 316 L was selected for the majority of components comprising the pilot system.

1.2 Research Scope and Objective

The goal of this study is to create a guideline and methodology that can be used to select optimal materials for renewable ocean energy projects. The current study only addresses the selection of alloys, but any material can be added to the database and analyzed in the same manner. Thus, an optimized material selection can be accomplished for any component of any of the energy projects at FAU, provided that the requirements of the components are clearly defined and the database is updated with the proper materials and relevant properties.

The background and literature review chapter is divided into three main subject areas: 1) Material Selection Factors, 2) Identifying Candidate Materials, and 3) Optimization of Material Selection. This chapter establishes what key material attributes are necessary for renewable ocean energy projects, identifies specific alloys that meet these requirements, and compares several recent material selection methods to determine the most suitable one for the application at hand.

The third chapter describes the chosen fuzzy logic material selection procedure in detail. It identifies the key components of the MATLAB fuzzy logic toolbox and how they can be used to evaluate materials for use in engineering designs.

The fourth chapter presents a case study material selection using the fuzzy logic material selection procedure. The case study evaluates candidate alloys for use in four of the major components in the ocean kinetic energy conversion system. The case study is presented in a detailed, step-by-step manner, taking the reader through the entire material evaluation process.

The fifth chapter reevaluates the case study selections from the previous chapter by comparing them with a proven and reliable material selection method. By comparing the fuzzy logic method with a standard material selection method the validity and reliability of the fuzzy logic method is assessed.

The sixth chapter discusses the implementation of fuzzy logic systems while the seventh chapter draws conclusions about the case study and the validity of the described fuzzy logic method. The strengths and weaknesses of the method are discussed.

2 Backgrounds and Literature Review

2.1 Material Selection Factors

Proper material selection is paramount to the success of any engineering endeavor, no matter the scale. The performance of a material in a marine environment depends on the service parameters, choice of materials, corrosion control methods, the type of environment and design configurations [2]. The importance of proper material selection is magnified in the case of renewable ocean energy, given the corrosive nature of the working environment and that there is no preceding example to base decisions off of. The materials chosen for each component in a system must meet all performance requirements, ensure a long working life of the system with minimal or no required maintenance, and be cost effective. The most important factors to be considered when selecting materials for renewable ocean energy projects are strength, toughness, high resistances to corrosion and biofouling, thermal conductivity, weldability, machinability, and cost.

2.1.1 Corrosion and Biofouling

Corrosion and biofouling resistances are of the utmost importance when selecting materials. The ocean environment is a very corrosive one and can cause severe biofouling problems. The possibility of corrosion is controlled by thermodynamics and the rate of corrosion is controlled by kinetics. The thermodynamics of a reaction are dictated by the half-cell reactions. Corrosion rate in seawater is dependent upon temperature, oxygen content, salinity, water chemistry, pH, biofouling, pollution, galvanic interactions, fluid velocity, alloy composition, alloy surface films, geometry, surface roughness, and heat transfer. These characteristics can be grouped into three broad categories, physical, chemical, and biological [3].

The high electrical conductivity of seawater promotes the electrochemical reactions that are responsible for all types of corrosion. The temperature of the environment has several effects on corrosion as well; increasing the temperature increases the conductivity of seawater. A temperature increase of 10° C commonly doubles the rate of diffusion, which is a limiting factor in many corrosion reactions. Temperature also increases the dissolved oxygen content of seawater, which has different effects on the corrosion rate of different materials. The water off the coast of southern Florida is warmer and typically contains a higher concentration of sodium chloride than most bodies of saltwater on the planet. The higher sodium chloride content increases the effects of all types of corrosion.

There are two processes operating simultaneously in the seawater environment: formation and repair of passive films on alloy surfaces due to the presences of dissolved oxygen, and breakdown of passive films due to chloride ion activity [4]. There are four ways a metal may passivate in aqueous solutions: the air film formed prior to immersion, a salt film, chemisorption of the solvent, and an oxide formation [2]. The formation of passive films reduces ionic transport of reactive species causing corrosion. The breakdown of passivity is associated with a critical potential, the presences of aggressive species and discrete areas of attack.

Oxygen content is an important factor in the stability of passive oxide films that are vital to the performance of materials such as stainless steels and aluminum alloys. The solubility of oxygen varies inversely with temperature. Oxygen content also varies with depth. Typically the oxygen content is at a maximum at the surface and then decreases to a minimum at about 700 m depth [5]. However, at warm sites, the surface oxygen is lower and below the oxygen minimum zone can actually increase above levels at the surface. If the oxygen content is known, the corrosion behavior can be predicted, even without a thorough understanding of the processes involved.

The degree by which dissolved oxygen influences corrosion is dependent on the alloy. Oxygen is favorable for passive film forming alloys, however, in fully aerated water, surface deposits on passive film-forming alloys can create oxygen concentration cells, which can cause pitting or crevice corrosion. For irons and steels, corrosion increases with increasing oxygen content. Dissolved oxygen increases corrosion rates in copper alloys under fast flowing conditions.

Biological organisms can affect materials physically; the films of organisms that attach to surfaces in marine environments inhibit diffusion and can damage protective coatings. Biofilms can form environments on the surface of metals that are very different form the bulk fluid and may cause reactions not predicted thermodynamically. Sometimes these biofilms cause a noble shift in open circuit potential of stainless steels, nickel, and titanium alloys. Barnacles can create differential cells that cause crevice corrosion. Sea urchins “graze” metal surfaces removing corrosion products that normally inhibit corrosion. The higher than average annual temperature of the water in South Florida leads to a greater number of micro-organisms present which increases biofouling concerns for renewable energy projects.

The number and types of organisms found in deep water are very different from those found in near-surface waters. There are far fewer macro-organisms in deep water and most of these live near the bottom sediments feeding on accumulated detritus. Biofouling rates are much lower in deeper waters and are often negligible.

Ocean currents affect the corrosion rate of metals directly through the effects of velocity and indirectly by bringing ocean masses with varying chemical characteristics. Flow rate also effects the corrosion and biofouling of alloys. However, this effect is a complicated one. The influence of flow rate on corrosion is a prime concern because it impacts different alloys in different ways. The Gulf Stream Current has a high enough flow rate to cause the hydrodynamic removal of normally adherent product films that are responsible for the resistance to corrosion of many alloys. Conversely, on other alloys a higher flow rate decreases the affects of pitting corrosion and can remove the build-up of aggressive ions.

Ocean structures extending through the tidal zones illustrate the effects of the environment on corrosion and the interaction between materials exposed to different environments. In the splash and spray zones, the distribution of sea salt and the high availability of oxygen can cause high corrosion rates. In the intertidal zone, corrosion rates are often low due to the oxygen concentration cell between the intertidal zone and the fully immersed zone. If the structure is steel the intertidal zone will be cathodic to the steel in the fully submerged zone [6].

The mechanisms of corrosion do not change in deep-water conditions. However, in deep-water ionic concentrations are expected to be lower due to the enormous solvent volume. Such a decrease will cause regions of passivity to shrink on the Pourbaix's Diagram, and thus corrosion is more likely. This is because a lower ionic concentration in the seawater means the total ionic concentration is further from the solubility limit and there is more room for generation of metal ions [3]. However, the decrease in temperature in deeper water will cause the regions of passivity to expand. Also, water stability regions on the Pourbaix's Diagram expand with increasing depth.

Corrosion and biofouling resistances of materials are complex and vary, often drastically, in different environments. For most components of ocean energy projects good corrosion and biofouling resistances will be one of the most important attributes governing material selection. Information for specific materials concerning these resistances will often be unstructured and non-quantitative. Much attention will have to be paid to how a candidate material will perform in the intended service environment, joined to the other components of the system.

2.1.2 Strength and Fatigue

Due to the magnitude and cyclic nature of wave loading, much of the development of the science of fatigue and fracture has been promoted by problems encountered in the marine environment [7]. Virtually any component in an engineered system will bear some magnitude of loading and experience some cyclic loading.

Strength and resistance to high cycle failure are important attributes for almost any component, and especially important in the ocean environment, where dynamic loadings are always present. Factors that need to be considered and analyzed are pressure loads, hydrodynamic loads, the possibility of hydrogen embrittlement, fatigue-corrosion relation, high cycle fatigue load behavior, dynamic response of the structure to loading, and fracture toughness of the materials. As with most engineered components, bending will usually control over compression, and stiffness requirements and deflection limitations must be considered and incorporated into materials selection [8].

2.1.3 Thermal Conductivity and Thermal Expansion

Thermal conductivity and thermal expansion are material properties that cannot be overlooked in the material selection process. Some components require a material that can quickly dissipate heat so that the system does not over heat and functions properly. Many systems require pipes with good insulation so fluids maintain the correct temperature, such as a deep water pipe used to carry cold water in the OTEC process. Knowing how a material will expand or contract in systems where temperatures change drastically is important so that components maintain the proper orientation and fit.

These physical properties can influence the way passive films resist corrosion. Too much thermal expansion can cause passive oxide surface films to tear, and localized corrosion to occur [2]. The thermal conductivity and thermal expansion of candidate materials need to be incorporated into the material selection process for every system and component.

2.1.4 Weldability and Machinability

Weldability and machinability are important parameters in any material selection, and even more so in new and developing applications, like renewable ocean energy, where most components won’t be mass produced at first. The demands of fabrication are crucial in any marine related project and impact the cost of the project directly [7]. Therefore fabrication will have to be considered as a material property and as a variable impacting cost.

Due to the requirements of load bearing capacity and fatigue resistance, welded fabrication is often necessary. Weldability and machinability of materials have a direct impact on both the cost and timeline of a project. High strength welded structures are very susceptible to hydrogen damage. Failure of welds can occur due to environmentally assisted cracking resulting from applied stresses and hydrogen embrittlement. Weld joints have three different zones: the cast weld zone, the heat affected zone, and the parent metal [9]. Welding defects can have a dynamic effect on the corrosion resistance of welded joints. Special care will have to be taken when welding components for renewable ocean energy projects to ensure they maintain the required strength and corrosion resistance.

Factors affecting how easily an alloy can be welded include material composition, thermal conductivity and thermal expansion [10]. Depending upon the material composition a certain amount of heat will be required to weld an alloy. The less heat necessary the more easily the material can be welded. The lower the value of thermal conductivity the easier it is to weld an alloy. This is because high thermal conductivity allows the heat to spread through the metal, requiring more energy to weld. A lower value of thermal expansion is desirable when welding so that the heated area doesn’t contract and weaken while cooling.

2.1.5 Cost Effectiveness

A project must be cost effective in order to be successful. Start up cost compared to the working life and cost of maintenance of a project is a primary consideration when selecting materials [11]. Alloy surcharge rates can be used to help estimate cost, but the cost of materials is constantly fluctuating due to economic variations. In recent history the price of the metals used in corrosion resistant stainless steels and nickel alloys have fluctuated widely. From March 2006 to March 2009 the price of nickel jumped from \$6.75 per lbs to over \$23.00 per lbs and fallen back to \$4.30 per lbs [12]. Similar fluctuations have occurred with cobalt and molybdenum. The price of these metals is driven by the world economy and is impossible to predict. At the start of a material selection the user should update the candidate materials in the materials database to reflect current prices and availability.

2.2 Identifying Candidate Materials

One of the main purposes of the literature review is to identify suitable materials for use in a variety of renewable ocean energy applications. Strength, ductility, thermal conductivity, thermal expansion, corrosion resistance, biofouling resistance, and high cycle fatigue behavior of the materials were analyzed and compared in the various reviewed articles. The focus of this segment of the literature review is mainly geared towards corrosion resistant alloys, alloys used in OTEC applications, and amorphous metallic glass coatings.

2.2.1 Stainless Steels

There are five main types of stainless steels ferritic, martensitic, austenitic, precipitation hardening, and duplex. Each of these five has a subset of super families, such as a super austenitic or super duplex. Most ferritic and martensitic stainless steels have limited corrosion resistance in seawater, except for some of the recent super ferritics. Austenitic stainless steels are iron-chromium-nickel alloys. Through additions of molybdenum and nitrogen they can achieve excellent corrosion resistances. The precipitation hardening stainless steels are nickel-chromium-iron alloys that have higher strength than the austenitics but have less ductility and are more susceptible to corrosion. The duplex stainless steels are iron-chromium-nickel alloys that contain a 50-50 mix of ferritic and ausenitic crystal structures [13]. The strength of duplex stainless steels is roughly twice that of common austenitic stainless steels. Many duplex stainless steels have excellent resistance to corrosion in the marine environment [14]. The austenitic, super austenitic, duplex, super duplex and super ferritic alloys are the stainless steels typically used in marine applications.

Stainless steels get their corrosion resistance from a thin, invisible, passive layer on the surface of the alloy. The degree of protection afforded by such an oxide is a function of the thickness of the oxide layer. Oxygen content is an important factor in the stability of passive oxide films that are important in the performance of materials such as stainless steels and aluminum alloys. The solubility of oxygen varies inversely with temperature [15]. If the passive film is continuous and remains stable, the alloy will resist corrosion. If the film is not continuous localized corrosion in the form of pitting or crevice corrosion may initiate and propagate rapidly. Embedded iron and heat tinting are two common surface defects that can result in reduced corrosion resistance [16]. Care must be taken to prevent their formation.

Types 304 and 316 stainless steels have adequate corrosion resistance for many mildly corrosive marine applications. However some applications require more corrosion resistance. Stainless steels with a PREN greater than 40 are generally considered to be very corrosion resistant in most marine applications. Crevice corrosion resistance is frequently the limiting factor for stainless steels in marine service. Duplex alloys with a PREN over 40 are highly resistant to crevice corrosion. They are also more resistant to chloride ion stress corrosion cracking than austenitics. The cost of stainless steels is roughly proportional to their corrosion resistance [14]. It is important to select an alloy with sufficient but not excessive corrosion resistance for this reason.

The relationship between depth and corrosion rate in stainless steels is a complicated one. There is evidence to suggest that stainless steel corrodes at a much higher rate in warm surface waters than in colder deep sea waters. In some cases stainless steel has been found to corrode many times faster in warm surface water than in colder deep sea water [17]. However, other research has concluded that corrosion rates only vary slightly with depth [3]. Researchers do agree that in deep water, corrosion of stainless steels is generally not related to any biological product but mainly to the electrochemical reaction of the alloys with the sea water, and propagation rates are slower.

Critical crevice indices and critical pitting indices can be used to rank similar materials such as rolled stainless steels. With respect to pitting corrosion, the same index can be used for duplex and austenitic stainless steels. With respect to crevice corrosion different indices must be used [18]. Crevice corrosion of highly alloyed stainless steels exposed to natural seawater can propagate at temperatures far lower than the initiation temperature. Therefore, repassivation properties of a material are important for material selection and corrosion control. The differences in heat treatment and product form can be far greater than minor variations in chemical composition. Cast materials, in general, show less corrosion resistance than forged or rolled materials.

Alloy composition greatly influences a stainless steel's corrosion resistance. An index used to determine an alloy's resistance to localized corrosion is the pitting resistance equivalent number, or PREN. A PREN greater than 40 is generally considered adequate to avoid pitting attack [14, 19]. The PREN is generally calculated as follows, although slight variations exist.

$$\text{PREN} = \%\ \text{Chromium} + 3.3 \times \%\ \text{molybdenum} + 16 \times \%\ \text{nitrogen}$$

Numerous studies demonstrate the beneficial effects of raising Cr, Mo and N contents on the localized corrosion resistance of stainless steels in seawater at ambient conditions.

Ocean environments change greatly depending on location and depth. Flow rate, temperature, oxygen content, chloride content, and biological activity vary greatly from place to place. Stainless steels are relatively insensitive to mildly flowing seawater but severe jet impingement can reduce the corrosion resistance drastically for some of the less resistant alloys. Studies indicate that the corrosion behavior of higher alloyed stainless steels is not sensitive to an increase in salinity. In contrast, higher salinity water is more aggressive towards the lower alloyed stainless steels [20].

Ennoblement of the corrosion potential for passive metallic materials takes place during exposure to natural biotic seawater below 40° C. Biofilms formed on stainless steels after immersion in natural waters, in the absence of localized corrosion, raise the corrosion potential from initial values below 0 mV to values from 300 mV to 500 mV [9]. The corrosion potential evolves with time and its increase raises the likelihood of localized corrosion. Localized corrosion manifests itself through steps of initiation, repassivation and propagation phenomena. The cathodic current density of stainless steel polarized to -100 to +100 mV is a very sensitive indicator of the bioactivity occurring on the surface [21]. During the period where the open circuit potential is rising, susceptibility to localized corrosion is at a maximum. There is a critical temperature at which crevice corrosion begins to initiate and a lower critical repassivation temperature.

Much research has been performed on stainless steels for use in OTEC applications. The findings from these studies can be applied to all renewable ocean energy projects. Ferritic Stainless steels show good corrosion resistance in OTEC studies. Super ferritic stainless steels are strong candidates due to their excellent resistance to pitting and crevice corrosion. In Darby’s study, of the stainless steels tested alloys 29-4C and Monit appeared to be the most resistant [22]. Al-6X and SC-1 also appeared to have adequate resistance to crevice corrosion in an OTEC plant. Alloy AL-6X (2Cr-25Ni-6Mo) is an alloy that shows excellent corrosion resistance, and has been qualified for

OTEC heat exchangers [23]. It is used in numerous power plants for seawater cooling and has comparable performance with titanium alloys.

Proper gasket selection is important when using stainless steels. Improper selection can lead to leaks resulting in failure of the system. For high-alloy stainless steels in seawater gaskets made of synthetic rubber, rubber bonded aramid, or synthetic fiber should be used. The use of PTFE or graphite-loaded gaskets should be avoided. For high pressure systems up to 100 bar graphite-containing gaskets are acceptable provided the graphite is sealed from the seawater and is never wetted [24].

Experimental results show that the corrosion potentials of lower alloy stainless steels, like Type 316L, are typically more positive than their repassivation potentials in seawater. This results in localized corrosion of the alloy. Conversely, the corrosion potentials of higher alloy stainless steels, like alloy 254SMO, are typically more negative than their repassivation potentials in seawater. Thus, they are expected to be resistant to localized corrosion.

2.2.2 Nickel Alloys

In the 1940's nickel chromium alloys entered the marketplace. Around the same time additions of iron and molybdenum were being experimented with. The resulting alloys were used in a variety of chemical plants. Additions of Ti, Al, W, and Nb to the nickel alloys yielded high strength alloys, the first of which was K-500. In recent years several high strength nickel alloys have been developed for marine use, including 718, 625, 725, and 925. The most corrosion resistant family in the marine environment is the C family, which have 16-24% Cr and 14-16% Mo. Alloys C-4, C-276, C-22, 686 and 59 comprise this group [14]. The corrosion resistance, bio-fouling resistance, heat conductivity, and ease of fabrication of these alloys make them a viable option in traditional and innovative marine applications.

Nickel and nickel alloys have useful resistances to a wide variety of corrosive environments that are often too severe for other commercially available materials. In cases where more corrosion resistance is required, nickel alloys with a PREN greater than 50 show excellent resistance to crevice corrosion [25]. Nickel alloys are highly resistant to hydrogen embrittlement and stress corrosion cracking. They also show much better corrosion fatigue resistance than the austenitic stainless steels. Nickel alloys are unaffected by depth; alloys that are susceptible to crevice corrosion remain susceptible at any depth.

Seawater corrosion potential ennoblement can occur in nickel alloys that are resistant to seawater pitting but are poor oxygen reduction surfaces. This manifestation can cause corrosion potentials in excess of 300 mV. The biofilm-derived electrochemistry provides an alternate oxygen reduction pathway on passive film surfaces and is linked to increased localized corrosion in nickel-base alloys [26].

Alloy 400 has many advantages to commercially pure nickel; the addition of iron significantly improves the resistance to cavitation induced erosion. Alloy 400 is used in conditions of high flow and erosion as in propellers, shafts, casings, condenser tubes and heat exchangers. Its corrosion rate in flowing seawater is generally less than 0.025 mm/year. Alloy 400 is generally immune to stress corrosion cracking. Alloy 400 has been used to clad offshore structures in highly corrosive zones [27]. Nickel-copper alloys are used in a variety of marine based applications with excellent results.

Alloy K-500 is the age hardened version of alloy 400 with benefits such as improved strength and hardness. This alloy is primarily used in marine and oil and gas applications. Alloy 825 is a modification of alloy 800 with the addition of molybdenum, copper and titanium providing improved aqueous corrosion resistance. The 6Mo nickel alloys have increased molybdenum content and the addition of nitrogen to improve localized corrosion resistances. The 6Mo alloys have extensive uses in marine and offshore applications. These alloys' compositions are listed in the Tables of Appendix A.

Out of the “C” family, alloy 59 has the highest chromium plus molybdenum content and the lowest iron content. It has one of the highest allowable stresses and great corrosion resistance. Alloy C-276 remains the most used and commercially available of the “C” family. The “C” family is used in a variety of marine applications [28].

Because of the size and working environment of marine fasteners they are often anodic to the surrounding structure. Therefore they must be very corrosion resistant in order to resist the effects of galvanic and crevice corrosion. Thus, highly corrosion-resistant nickel based alloys have been used extensively in the marine environment.

Monel K-500 alloy fasteners are commonly used with steel in seawater environments, but in extreme situations the resulting galvanic coupling can induce hydrogen charging and cause embrittlement of the fasteners. Inconel alloy 686 is a nickel-base alloy that exhibits high tensile strength and fracture toughness, as well as excellent corrosion resistance when used as a fastener in the marine environment. It achieves this excellent performance through a unique combination of chromium, molybdenum and tungsten [29].

2.2.3 Aluminum Alloys

Aluminum alloys depend on an oxide film for corrosion resistance. Under some circumstances and for some alloys corrosion rates can be quite low in marine environments. The rate of pitting depth in aluminum alloys increases as oxygen and pH decrease. The main reason for the use of aluminum alloys in any environment is their high modulus to density and yield strength to density ratios [7]. Aluminum alloys have very high thermal and electrical conductivities and moderately high coefficients of thermal expansion.

Aluminum alloys have long been used in the marine industry. Aluminum is attractive because of its low cost, but its corrosion resistance in seawater is less than that of most nickel and stainless steel alloys [30]. Protective measures and frequent maintenance is required. An OTEC plant built from aluminum alloys would have an expected life of 10 to 15 years [23]. Prime candidates for OTEC applications are alloys 5050, 5052, 6061 and 6063.

Due to their dependence on passivity, aluminum alloys have a tendency to suffer localized attack. Stress corrosion cracking is a problem in many aluminum alloys and care should be taken to avoid coupling with noble metals due to the high electronegative nature of aluminum. Aluminum alloys perform better in warmer surface waters with higher pH and oxygen content. In colder water aluminum alloys show intense pitting [17]. Their use should also be avoided in stagnant or slowly flowing marine environments, again, due to an increase in pitting corrosion.

Copper is added to aluminum to increase strength, but it is detrimental with regard to corrosion resistance, even in concentrations less than one percent [31]. Microscopic corrosion cells form around the copper particles and the adjacent aluminum is corroded away. In general, aluminum alloys used in marine service should not have additions of copper.

2.2.4 Copper Alloys

Copper alloys possess exceptionally high electrical conductivity, thermal conductivity, and resistance to biofouling. These properties have resulted in the wide use of copper alloys in marine heat exchangers and power plants. Unlike other alloys, copper corrodes actively in seawater. However, the process is controlled by a resistive anodic corrosion product film and not oxygen availability [19]. Copper based alloys used in marine service are typically, bronzes, brasses, and cupronickels.

Offshore structures have been clad in highly corrosive zones using copper-nickel alloy C70600 [27]. Corrosion resistance, bio-fouling resistance, heat conductivity, and ease of fabrication of copper-nickel alloys make them a viable option in traditional and innovative marine applications.

Copper alloys have a low corrosion rate which varies little with depth. Copper and Cu-Ni alloys corrode more rapidly in colder deep-sea water but level off quickly, so that after a long period, little difference exists between the cold deep water and warm surface water [17]. However, copper corrodes much faster than Cu-Ni and is much more likely to suffer from pitting attack [32].

Velocity induced corrosion can be a serious problem for copper alloys. Flow rates above the critical breakdown velocity damage the protective film and attack is rapid. Geometry can have a significant affect on the flow-assisted corrosion rates of copper alloys. As pipe bend radii are reduced the corrosion rate will increase. The critical velocity at which corrosion becomes a problem in 90/10 Cu-Ni is 3.6 m/s for large pipe sizes and as low as 34% of this value for very small pipe diameters [7].

Copper alloys are also susceptible to dealloying and stress corrosion cracking. Environments with ammonia and hydrogen sulfide are particularly deleterious to these corrosion forms [19]. Polluted waters contain hydrogen-sulfide and sulfate containing compounds, both of which are known to adversely affect the corrosion of some metals. Sulfide corrosion has been found to occur on a number of different copper-base alloys [2]. Copper-base alloys were deemed unusable as heat exchanger materials for OTEC systems, due to their susceptibility to erosion attack when exposed to ammonia, which is the best working fluid for a closed cycle OTEC plant [22].

2.2.5 Carbon and Alloy Steels with Secondary Protection

Carbon steels have good toughness and ductility and are employed in the vast majority of structural applications. Alloy steels contain additions of Ni, Cr, and Mo which improve hardenability and strength. However, susceptibility to stress corrosion cracking and hydrogen embrittlement generally increases with increasing strength. The fundamental limitation of carbon and alloy steels is that they corrode actively and uniformly. Corrosion products develop within a brief period unless mitigated by coatings or cathodic protection [19]. Steels have a dramatic reaction to increasing depth in that their performance decreases with increasing oxygen content.

Organic coatings are the most commonly used form of corrosion protection with cathodic protection being used as back up. The function of a coating is to provide an environmental barrier to the underlying material, preventing corrosion. Both organic and metallic coatings require good surface preparation in order to function properly. It is all but impossible to maintain 100% integrity in any organic coating. Metals that have noble solution potentials cause intensified attack of active unalloyed steel or aluminum. Anti-fouling coatings work by continuously releasing toxins at a low rate. Typical toxins used for deep-water protection are cuprous oxide and tributyl tin oxide. Coating thickness for deep ocean structures is usually around 0.015 in [3].

Corrosion is an electrochemical process and therefore electrode potential can be used to control the reaction rate. Cathodic protection is the most efficient and effective way to control corrosion for submerged alloys. Cathodic protection either employs a sacrificial anode, usually zinc or aluminum, or utilizes an impressed current to protect a structure. The electrochemical behavior of the cathode and anode are influenced by water depth, dissolved oxygen, temperature, salinity, pH, sea current, pressure and fouling. Coatings tend to distribute cathodic currents more uniformly. On non-coated surfaces cathodic protection causes the build-up of protective calcareous deposits which can lower current demand in natural seawater.

Three sacrificial anodes are used in marine cathodic protection, Zn, Al, and Mg. However, impressed current cathodic protection is more commonly used in the deep-sea environment. 5 mA/ft^2 current-density is required to protect bare steel in quiet seawater. A 12 lbs zinc anode can protect 100 ft^2 of steel for 14 months [3]. A good vinyl paint can reduce the current requirements five-folds.

Hydrogen can enter ferrous alloys in a variety of ways and promote degradation. Hydrogen can be picked up from residual water during welding where it diffuses into the hot welded area. Embrittlement then occurs when the weld cools by cold cracking in the weld heat affected zone. Hydrogen embrittlement can also be caused by improperly performed cathodic protection where hydrogen ions are produced and absorbed into the protected metal [33].

The susceptibility of high strength steels to hydrogen is related to their tensile strength and the binding energies of specific trapping sites [2]. Hydrogen embrittlement can result in catastrophic failure and care should be taken to avoid it. Typically, if the open circuit potential of an alloy is kept below -0.85 V vs. SCE by cathodic protection, hydrogen embrittlement will not occur.

2.2.6 Amorphous Metallic Glass Coatings

In metallic glass coatings, chromium, molybdenum and tungsten provide the corrosion resistance while boron enables the glass formation and rare earth metals such as yttrium lower the critical cooling rate [34]. Rare earth metals do have the side affect of making pneumatic conveyance during thermal spraying difficult due to the powders having an irregular shape. SAM1651 is a pore-free thermal spray coating produced with improved amorphous metal formulations and shows no corrosion after more than 30 cycles in the salt fog test. SAM1651 has similar corrosion resistance to that nickel-based alloy C-22.

The attributes of metallic coatings can be tuned to deliver corrosion inhibiting functions by a selection of alloy compositions and nanostructures. Coatings can be made to function as a local corrosion barrier, serve as a sacrificial anode, and supply soluble ions used as corrosion inhibitors [35].

2.2.7 Summary of Candidate Alloys

Because most of the components for renewable ocean energy systems will be constantly submerged, corrosion and biofouling resistances will be at the heart of most material selections. Stainless steels and nickel-base alloys as a whole have the best corrosion resistance and strength of the alloys researched. Their cost generally increases with increasing corrosion resistance, thus the more expensive alloys should be reserved for critical components. For stainless steels a Pitting Resistance Equivalent Number, or PREN, greater than 40 is generally considered adequate to avoid pitting attack. For nickel alloys a PREN greater than 50 is considered adequate to avoid pitting attack.

Aluminum alloys, while limited by their corrosion resistance, should be considered for components requiring a high strength to weight ratio. Copper alloys should be considered for components requiring a high thermal conductivity or biofouling resistance, although caution should be taken to avoid critical flow velocities and environments containing ammonia or hydrogen sulfide. If a carbon or alloy steel is employed, both a coating and cathodic protection for the system must be carefully selected and implemented.

Design also plays a substantial role in the performance of a material. Possible sites of crevice corrosion must be carefully considered and eliminated or minimized for all components. Materials must be compatible with one another or galvanic corrosion will occur. Ultimately the correct material selection depends on the environment and function of the component and candidate materials must be selected and analyzed with this in mind.

2.2.8 Material Database Spreadsheets

The compiling of a material database is the starting point for any material selection. A large number of corrosion resistant candidate alloys have been identified and organized into tables listing key physical and mechanical properties requisite to performance in the ocean environment. Selected materials include austenitic stainless steels, duplex stainless steels, ferritic stainless steels, nickel and nickel-copper alloys, aluminum alloys, and copper alloys. Additional tables listing their composition are also included.

This database will help to easily compare and analyze the materials for use in specific components and systems. The database is in spreadsheet form so that materials and their attributes can be evaluated simultaneously using analytical material selection methods. The database can easily be expanded to include any desired material if the user has adequate knowledge of the material and its properties. This database is presented in Appendix A.

2.3 Optimization of Material Selection

The performance of a structural component is a function of the functional requirements, geometry, and material properties [36]. These parameters can usually be separated which makes the material selection independent from the details of the design. The selection of an optimal material for an engineering design from two or more materials is a multiple attribute decision making problem. Material selection relies on a unique synergy of theory and practical experience. This section examines some of the recent advancements in the ways materials are evaluated and selected for engineered systems.

2.3.1 Data Systems in Material Selection

In the development of a product designers will often conceive parts using processes and materials with which they are familiar. This often leads to the exclusion of more economic process and material combinations. The use of computer based data systems allows designers to easily search for materials based on desired attributes, which results in a more optimal selection of materials.

Structured materials information is generated by statistically comparing the results of individual test records to determine minimum values of properties which can be reliably used for design purposes [37]. Measured property values may then be combined to provide functional data. Such data is usually only available in the form of picture graphs, meaning it cannot be used in a quantitative selection process. Instead, the user must refer to the graphs individually, manually interpolating them for the relevant conditions.

Optimal material selection requires two types of information; screening and ranking information and supporting information [37]. Screening and ranking requires a database of structured information to be filtered, based on design requirements, to yield a list of candidate materials. Supporting information is used to narrow the list of candidates to a few prime choices.

Screening and ranking is usually quantitative and consists of shifting through the database based on the technical and economic requirements of a design. The two types of selection criteria are constraints and objectives. Constrains are design requirements that must be satisfied, such as a minimum strength. Objectives are design criteria that must be maximized or minimized to optimize the performance of the component.

Supporting information is typically non-quantitative and is likely to contain specialist information. This may be information about the microstructure, performance in a specific environment, or other phenomena. Large quantities of information may be available and is often very detailed. This information can be easily found in a research literature database or on the internet [38].

2.3.2 Material Selection Using Expert Systems

An expert system is software that is designed to reproduce the knowledge of a human expert and is an application of artificial intelligence. The simulation of the knowledge of an expert is accomplished by creating a knowledgebase which uses knowledge representation formalism to capture the subject matter expert’s knowledge [39]. That knowledge is then gathered from the subject matter expert and codified according to the formalism. This process is known as knowledge engineering. Once the system is developed it is proven by being placed in the same real world problem solving situation as the human subject matter expert.

Expert systems rely on inference rules to reason and come to conclusions. There are two main methods of reasoning when using inference rules: backwards chaining and forwards chaining. Forward chaining starts with the data available and uses the inference rules to conclude more data until a desired goal is reached. An inference engine using forward chaining searches the inference rules until it finds one in which the if clause is true, then adds the then clause information to its data. Backwards chaining starts with a set of goals and works backwards in that it searches the inference rules until it finds one which has a then clause that matches a desired goal [40].

One advantage of expert systems over traditional methods of programming is that they allow the use of confidences. These numbers are similar in nature to probabilities, but they are not entirely the same. They are meant to imitate the confidences humans use in reasoning rather than to follow the mathematical definitions used in calculating probabilities.

Expert systems are used in a wide variety of decision making problems. They have repeatedly been proven to work well in material selection applications to optimize both cost and performance of a component [39]. The foundation of a successful expert system depends on a series of technical procedures and developments that are designed by technicians and related experts. Thus, they require a large amount of time and effort to fully develop for even a relatively simple application.

2.3.3 Weighted Properties Method

In the weighted properties method each material requirement or attribute is assigned a certain weight depending on its importance to the performance of the given component [31]. A weighted-property value is obtained by multiplying the value of the property by the corresponding weighting factor. The individual weighted property values of each material are then summed to give a material index used for comparison with other materials. The higher the performance index, the more suitable it is for the given application.

While the weighted properties method is simple, it produces good results if the user has the requisite knowledge to weight requirements properly. The weighted properties method has the drawback of combining unlike units which can yield irrational results. This becomes a problem when different mechanical, physical and chemical properties with widely different numerical values are combined. The properties with higher numerical value will have more influence than are warranted by their weighting factors. This can be overcome by using scaling factors in which each property is scaled so that its highest numerical value equals 100.

2.3.4 Digital Logic Method

When a large number of material properties are considered in a selection, and the relative importance of each is not easily defined, determination of proper weighting factors can be difficult which reduces reliability of the selection. The digital logic method is used to systematically determine weighting factors for material requirements and properties [31].

In this procedure evaluations are arranged so that only two properties are considered at a time. Every combination of properties is compared in a matrix comprised of only yes and no decisions. To determine the relative importance of each property a table is constructed with the properties listed in the left hand column and comparisons being made in the columns to the right. The total number of positive decision in the matrix is summed and the sum of the positive decisions in each row is then divided by the total sum. The resulting number for each row is the relative emphasis coefficient, which is the correct weighting factor to use for that corresponding property [31].

To increase the accuracy of decisions using the digital logic approach the yes no evaluations can be changed to gradation marks, ranging from no difference in importance to a large difference in importance. In this case the total gradation marks for each selection criterion are reached by adding up the individual gradation marks. The weighting factors are then found by dividing each row's summed gradation marks by the grand total in the matrix.

2.3.5 Ashby Method

As pressure to reduce product development time and cost increases, the need for an integrated approach of product design, materials selection and economic analysis also increases. An efficient way to optimize both material performance and cost is the Ashby method, developed by Michael Ashby at Cambridge University in the mid 1990's. The use of selection charts, performance metrics and exchange constants is at the core of the Ashby Method. The Ashby Method is simple to use and contains basic ideas that have been expanded upon by other researchers.

The Ashby approach is led by design. The first step is to determine what the function of the component in the design is. This leads to defining the objectives of the material that need to be optimized and the constraints of the material that need to be satisfied. An objective is a goal that maximizes performance, such as being as light or strong as possible. A constraint is a minimum value that a material must meet in order to be considered for selection [36].

The performance of a component is measured by performance metrics, which depend upon control variables that can represent any property of a material. Multi-objective optimization is a procedure for simultaneous optimization of several independent metrics. When choosing a material the goal is to optimize the metrics of performance in the product in which it is used. The difficulty is that the choice that optimizes one metric will not, in general, do the same for the others. It then becomes a compromise, trying to push all metrics as close to their maxima as their interdependence allows [41].

Material selection charts plot one material property against another. Every material in a dataset is represented as an ellipse showing the range of its possible values for either property. Material selection charts provide a graphical representation in which to apply and analyze quantitative selection criteria, like those expressed in performance metrics. These charts can also be used to make trade-offs between conflicting objectives

When there are two or more objectives they are usually measured in different units and will be in conflict with each other. If two objectives are plotted against one another several points exist on the graph, representing materials that have characteristics that no other solution exists with better values of both performance indices. These solutions are connected by a line or surface called an optimal trade-off surface [41].

The trade-off surface identifies the materials that have the best compromise between the objectives, but it does not distinguish between them. One can either choose a solution using intuition or by formulating a value function. A value function is formulated by multiplying each objective by an exchange constant and then adding them all together. An exchange constant measures the change in cost for a unit change of a given performance metric.

2.3.6 Fuzzy Logic Method

Optimizing complex combinations of technical and price properties is a hard process to achieve manually, so rational material selection software is an important tool. The use of fuzzy logic based analysis to optimize material selection is one of the recent innovations in rational material selection.

Material selection is a multi-criteria decision-making problem that involves trade-offs amongst decisive factors of material properties, manufacturing aspects, material cost, impact on the environment and availability. Fuzzy logic theory can be used to select the optimum material for a function from a pre-ranked group of materials based on relevant properties. This pre-ranking of materials is accomplished using expertise knowledge.

Fuzzy logic is a multi-valued logic which allows one to evaluate a set of variables by defining intermediate values between the conventional evaluation schemes such as true and false. It essentially enables computers a more human-like way of thinking. It requires the definition of fuzzy variables sets extracted from the physical problem [42].

At its core fuzzy logic is based upon fuzzy set theory. A fuzzy set is an expansion of the classical variable set between and including 0 and 1. A membership function is used to define how each element of the input space is assigned a value between 0 and 1. To evaluate a system fuzzy inference is then utilized. A fuzzy inference system is a framework that simulates the behavior of a given system using IF-THEN rules and is based off of expert knowledge or available data on the system. Rules are statements of knowledge that relate the compatibility of fuzzy premise propositions to one or more fuzzy spaces. In the case of a material selection the total number of rules is equal to the number of fuzzy sets raised to the number of material properties being considered.

Studies have been performed comparing fuzzy logic based material selections to other conventional methods of material selection [42, 43, 44]. Like other methods, fuzzy logic is used to calculate performance indices based upon material attributes. These performance indices are then used to rank the performance of candidate materials from best to worst.

Comparing fuzzy logic material performance indices with those of the leading non-linear methods it is evident that fuzzy logic material selection performs well. Fuzzy logic has been shown to identify the same top performing materials, based on design requirements of a component. The proper use of a fuzzy logic material selection method results in a wide spread of performance indices for the best to worst performing materials. The amazing thing about the fuzzy logic method is that is performs very similarly to the other leading material selection methods despite all its simplifications.

2.3.7 Summary of Optimization in Material Selection

The goal of a material selection is to simultaneously optimize performance and cost of a component for a given application. Utilizing data systems allows designers to easily search for materials based on desired attributes, making a wide range of materials data instantly accessible. Optimal material selection requires both structured data for screening and ranking of materials and supporting information to narrow this list of candidates to a few prime choices.

In the weighted properties method a weighting factor is calculated for each material requirement depending on its importance to the performance of a component. The weighted properties method has been proven to work well when there is a limited number of material attributes factoring into the decision. The digital logic method is a modified version of the weighted properties method in which weighting factors are systematically determined using a decision matrix comparing the relative importance of material attributes.

The Ashby method utilizes multi-objective optimization to simultaneously optimize several independent material performance metrics. Ashby also introduced material selection charts in which one material property is plotted against another. Material selection charts provide a graphical representation in which to apply and analyze quantitative selection criteria. A trade-off surface can be drawn on a selection chart so that each material on this surface represents an optimal combination of the objectives that no other material possesses. A solution is then chosen based of intuition or cost effectiveness.

Expert systems use artificial intelligence to reproduce the knowledge of a human expert. They rely on inference rules to reach conclusions and can include confidences based on probabilities. Expert systems have been proven to work well in material selection applications but can take a large effort to develop.

Fuzzy logic enables the evaluation of a set of variables by defining intermediate values between conventional evaluation schemes. Fuzzy logic theory can be used to select an optimum material for a function from a pre-ranked group of materials based on relevant properties. Like an expert system, fuzzy logic uses rules based on if-then statements to draw conclusions. The outputs from the fuzzy logic procedure are performance indices ranking the analyzed materials based on the stated rules. These rules, defined by the user, essentially describe the material requirements that optimize performance for the given application. Properly defining the rules and membership functions eliminates the need of weighting factors used in other selection methods. One of the mains strength of the fuzzy logic material selection procedure is its simplicity.

2.3.8 Development of the Fuzzy Logic Material Selection Method

The fuzzy logic approach to materials selection has been selected for further development to be used in this thesis with the foresight of being a design tool in renewable ocean energy applications. The MATLAB fuzzy logic toolbox is the employed software and the next chapter describes the details and nuances of its use. The fourth chapter presents a case study materials selection in which candidate materials are evaluated for use in four of the major components in the ocean kinetic energy conversion system.

3 Fuzzy Logic Material Selection Procedure

This chapter focuses on developing a method for the selection of materials using a fuzzy logic approach that can be used in renewable ocean energy applications. Fuzzy set theory is primarily used to deal with vague, imprecise and uncertain problems. It is therefore an excellent fit to aid in material selection in the relatively new and ill-defined frontier that is renewable ocean energy. The MATLAB fuzzy logic toolbox has been selected for development and implementation of this method because of its straight forward graphical interface system and overall ease of use. The described method is modeled after the work of Khabbaz, Manshadi, Abedian, and Mahmudi in developing a fuzzy logic approach for materials selection in engineering design [42].

3.1 Membership Functions

The first step in the material selection process is to specify the performance requirements of the component and outline the primary material characteristics required. Next the user will define membership functions for each of the required material attributes. These membership functions encompass ranges of performance using linguistic terms such as “bad”, “good” and “excellent”. The merit of material properties can be either qualitative or quantitative. Qualitative properties are easily matched with their corresponding membership function. For quantitative properties a fuzzy inference transforms the crisp inputs into a degree of match with the linguistic membership functions. Double sigmoid functions are utilized to match quantitative properties with corresponding membership functions. The membership functions and their corresponding sigmoid graphs are easily created and altered using MATLAB’s graphical interface system.

Figure 3.1 shows a graphical representation of an example membership function. The y-axis corresponds to the degree of fit within a membership function that an input variable (density of a material in this case) will have. The x-axis corresponds to the range of possible values an input variable can have. For example, if a material had a density of 4.0 g/cm^3 it would have approximately a 0.3 degree of membership with “excellent” and a 0.7 degree of membership with “good” in the membership function of Figure 3.1. In this way each material attribute of all candidate alloys are assigned degrees of membership in the selection procedure.

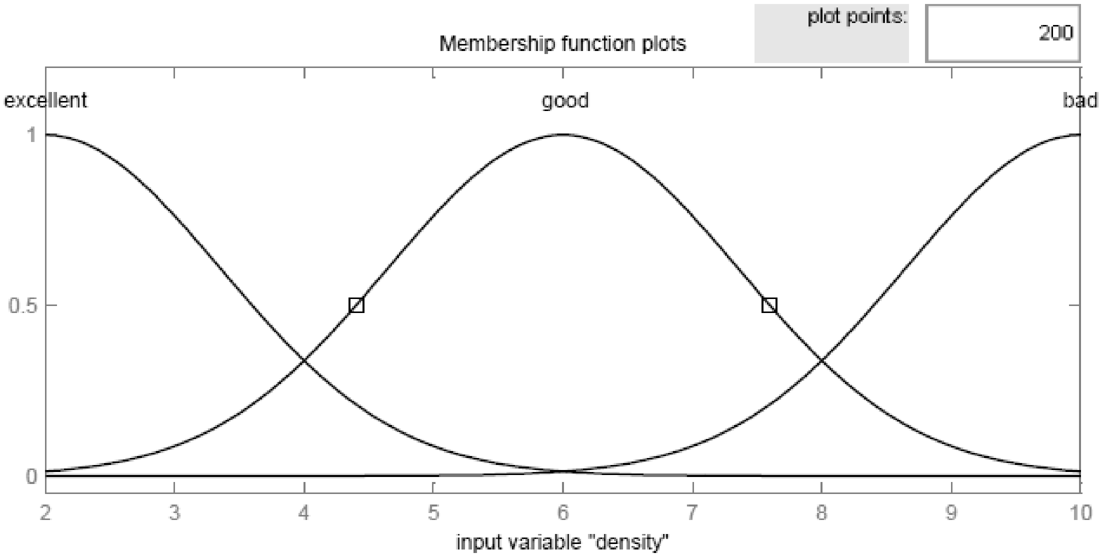


Figure 3.1: Example of Assumed Membership Function

3.2 Fuzzy Inference Systems

Fuzzy logic theory is then used to assign performance indices to each candidate material. This is accomplished by introducing a fuzzy inference system which simulates a given system using an expert’s knowledge. The fuzzy inference system evaluates each material using a set of simplifying rules, based upon if-then statements, relating the chosen material attributes to performance. The simplifying rules are basically statements of knowledge that relate the membership functions for each material property to the overall performance of the material for the specific application. These rules are easily created by the user with a graphical user interface. Typically, performance indices range from 0 to 100, with 100 denoting the best possible performance. A wide range of values in the resulting performance indices makes it easy to identify the top performing materials and is desirable. Table 3.1 shows an example of some assumed simplifying rules.

Table 3.1: Example of Assumed Simplifying Rules

	Price		Corrosion		Yield Strength		Weldability		Performance
IF	(B)	AND	E	AND	(B)	AND	(B)	THEN	E
IF	G	AND	G	AND	(B)	AND	(B)	THEN	G
IF	(B)	AND	E	AND	N	AND	(B)	THEN	G
IF	(B)	AND	B	AND	N	AND	B	THEN	B
IF	B	AND	B	AND	N	AND	N	THEN	B

B: bad, G: good, E: excellent, N: all conditions, ( ) : all conditions except

The simplifying rules cut down drastically on the number of expressions used to evaluate a system. Without simplifying rules, the number of rules to be defined is equal to the number of fuzzy sets used in the selection raised to the number of material properties being considered. For the example rules shown in Table 3.1, three fuzzy sets are used (bad, good and excellent) and 4 material properties are considered (price, corrosion resistance, yield strength and weldability). This means that there are $3^4 = 81$ possible expressions that could occur and a fuzzy rule needs to be defined for each. However, this number is drastically cut down using simplifying rules. As an example, the last rule shown in Table 3.1 states that if both price and corrosion resistance fall into the fuzzy set of “bad”, then performance will be bad no matter what the yield strength and weldability of the material are. This takes nine total expressions and reduces them to a single simplifying logic. In other words, all nine expressions that define both price and corrosion resistance as “bad”, result in a performance index in the “bad” range. The degree of membership with the “bad” fuzzy set for both price and corrosion resistance determines just how low of a performance index a material would be assigned. The more closely a combination of input values matches a defined simplifying rule, the more closely the assigned performance will match the defined output.

3.3 Assessing the Strength of Simplifying Rules

There are two graphical interfaces provided in the MATLAB fuzzy logic toolbox that aid the user in creating optimal simplifying logics, the rule viewer and the surface viewer. The rule viewer lists all simplifying logics using a graphical format and allows the user to see what overall performance index will be assigned based on any combination of inputs the user wishes to examine. This graphical interface is useful for making sure the simplifying rules accurately describe performance. As each of the material properties is altered, the user can observe how the performance index changes and see which of the simplifying logics controls. It is also useful for making sure there aren't any holes in the simplifying logics. Gaps are expressions that aren't covered by the simplifying logics and result in an undefined performance index. Figure 3.2 shows an example rule viewer. Note how the vertical lines denote the value of the material properties selected and also correspond to the degree of membership of each material property for the simplifying logics.

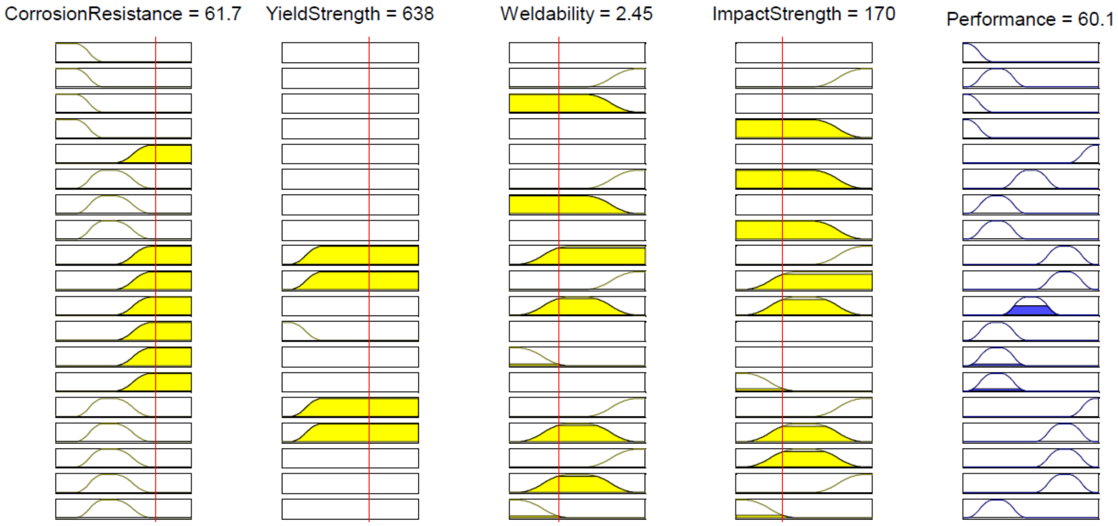


Figure 3.2: Example of Rule Viewer Interface

The surface viewer is a three dimensional plot that enables the user to examine the relation between performance index and any two material properties. The performance index always lies on the vertical axis and any of the considered material properties can be assigned to the two horizontal axes. The surface viewer allows the user to see how performance is connected to the two selected material properties, according to the created simplifying rules. The surface shown should increase from the lower corner, denoting the absolute least possible values of the two material properties examined, to the upper corner where these material properties are maximized. Flat regions will often occur, denoting areas where performance doesn't change inside these material property bounds, but should be kept to a minimum. However a reverse or negatively sloping surface should never occur. A negatively sloping surface means that as a material property is increasing, performance is decreasing. This indicates an error in the simplifying rules that needs to be fixed. Figure 3.3 shows an example fuzzy surface viewer. Note the smooth curves and gradual transitioning from the lowest to highest performance indices. A smooth surface is desirable and denotes that a performance index will gradually increase as the input variables are increased.

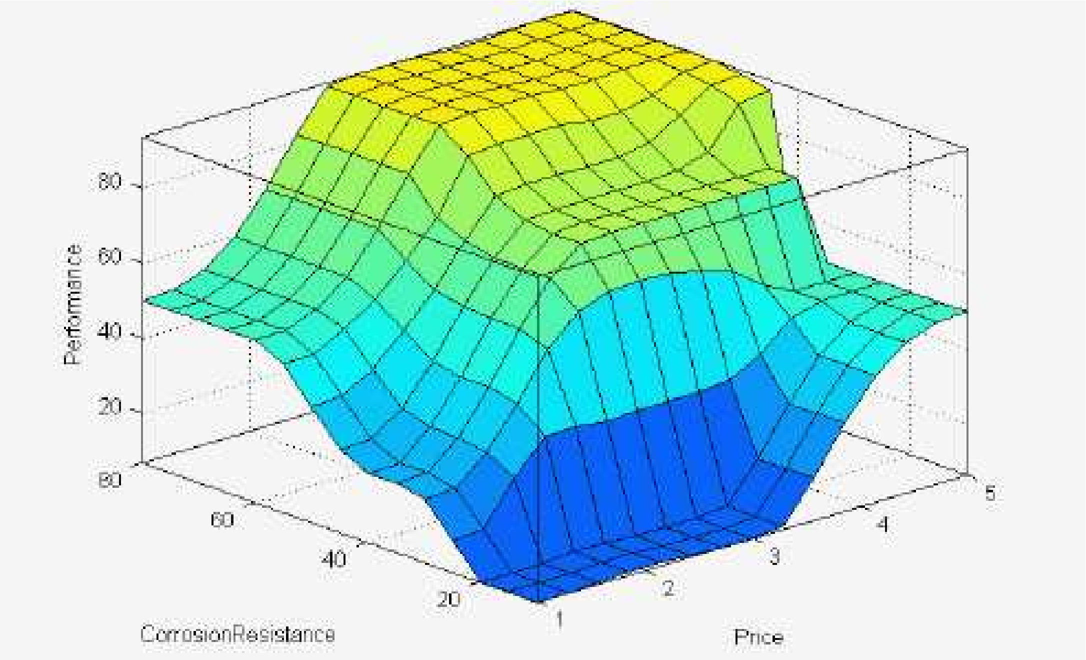


Figure 3.3: Example of Surface Viewer Interface

3.4 Quality of Results

The proposed fuzzy logic material selection method is user friendly and easy to learn due to its simple graphical interface system built upon linguistic terminology. The quality of a material selection using this approach is centered upon the user’s ability to define the function of the component in the design, assign proper membership functions for each material attribute contributing to this function, and formulate simplifying rules relating the chosen material attributes to the performance of the component.

In the next chapter a case study material selection is carried out, in detail, for a renewable ocean energy system being developed at Florida Atlantic University. The results are then analyzed and discussed, uncovering the strengths and weaknesses of the procedure as well as how and when it should be implemented.

4 Case Study Material Selections

In this chapter a case study is performed for the ocean current kinetic energy conversion system being developed at FAU. The four essential components chosen for this selection are the pressure vessel, turbine blades, drive shaft and connection gasket. The case study is presented in a step-by-step manner describing which material properties are chosen and why, how the membership functions are created, how the simplifying logics are selected and how candidate materials are then evaluated using the fuzzy selection system. For the following case study only stainless steel and nickel base alloys are considered due to their superior corrosion resistance and galvanic compatibility.

4.1 Material Selection for Pressure Vessel

4.1.1 Material Attributes Vital to Performance

The function of the pressure vessel in the kinetic energy conversion system is to provide a barrier between the inner workings of the ocean energy conversion system and the surrounding ocean environment. The pressure vessel will experience a variety of dynamic loadings and a constant hydrostatic loading. Thus, yield strength and toughness (expressed as charpy impact strength) have been selected as two of the fuzzy selection material properties.

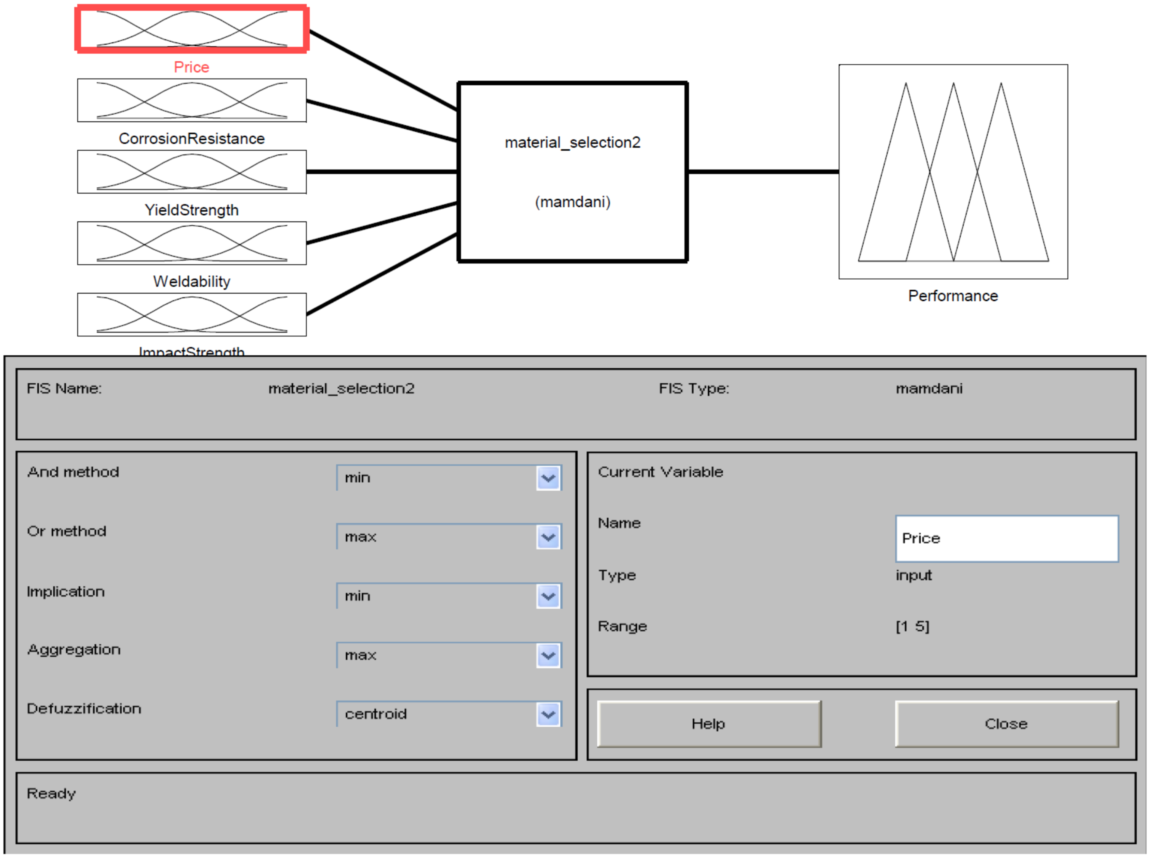
The service life of the system needs to be maximized; therefore the pressure vessel must be highly resistant to all forms of corrosion. Pitting resistance equivalent number is considered to be a gage of how resistant a material is to localized corrosion and has been chosen as a fuzzy selection material property. The PREN of a stainless steel and the PREN of a nickel alloy are determined in slightly different ways and therefore don't represent the exact same level of corrosion resistance. However, for the material selections presented here, the PRENs of the nickel and stainless steel alloys are assumed to be denote equivalent levels of corrosion resistance so that they can be compared on an equal footing.

The system will not be mass produced at first, so the ease with which all components can be welded is a major consideration. For this case study an index of weldability has been proposed, based upon the ease with which a material can be welded. This index ranges from 1 to 5, with 1 denoting a material that is difficult to weld and 5 denoting a material that is easily welded. This weldability index is another of the fuzzy selection material properties for the pressure vessel.

Cost is a very important variable when it comes to any material selection. The performance of a material must be compared to its price. For this first selection the impact of cost will be considered in two ways. First it will be included as a fuzzy selection material property and the selection will be carried out. In the second evaluation it will no be included as a material property; instead the performance of each candidate alloy will be normalized with respect to its price after the fuzzy evaluation. The results of these two methods will then be compared.

4.1.2 Creation of Membership Functions

The creation of membership functions to graphically represent the ranges of material property performance is an important step in the fuzzy selection procedure. Figure 4.1 displays the fuzzy input system (FIS) graphical interface used in the first material selection for the pressure vessel. The FIS interface is the first one a user will come to when opening the MATLAB fuzzy logic toolbox. From here the user can easily access the four other graphical interfaces of the fuzzy toolbox, add input and output



FIS Name: material_selection2

FIS Type: mamdani

And method: min

Or method: max

Implication: min

Aggregation: max

Defuzzification: centroid

Current Variable

Name: Price

Type: input

Range: [1 5]

Ready

Figure 4.1: FIS for Pressure Vessel

variables, and adjust the fuzzy evaluation settings. It is recommended that the "defuzzification" method is the default setting altered (The reason is explained in the following pages). The "and method", "or method", "implication" and "aggregation" settings should be left at the default settings of "min", "max", "min", and "max" respectively.

After much trial and error it is suggested that the user employs the pimf shape for all input and output membership functions. The pimf shape allows the user to select four points in the range of possible material property values to map a membership function to. To map the shape of a membership function the user selects four points like so:

[1.2 2.8 3.2 4.8]

The four numbers shown in the brackets assign the shape of the "good" fuzzy set in Figure 4.2, shown in red. The first number in the brackets assigns the beginning of the slope from 0 to 1 on the y-axis of the graph, emphasized in Figure 4.2 by a small box in the lower left corner of the plot. The second number assigns the termination of the positive slope into a plateau until the negative slope of the function begins at the third number in the brackets; these are emphasized by the boxes at the top of the plot. The final number in the brackets assigns the termination point of the slope, back to 0 on the y-axis.

Notice that the shape of the "good" fuzzy set is the exact inverse of the line comprising the "bad" and "excellent" membership functions. Thus, whatever value and input variable has, it will have a summation of 1.0 degree of membership with either one or two of the membership functions. For example if a price input variable had a value of

4.0 it would have a 0.5 degree of membership with the “good” fuzzy set and a 0.5 membership with the “excellent” fuzzy set. The most useful thing about the pimf shaped function is that the perfect inversion of fuzzy sets is easily maintained as the user adjusts the orientation of the fuzzy sets. To maintain the relative inversion the first two points of a pimf shape should match the last two points of the pimf shape to the left of it. So in the case of Figure 4.2, 1.2 and 2.8 are the last two points the “bad” function is mapped to while 3.2 and 4.8 are the first two points the “excellent” function is mapped to.

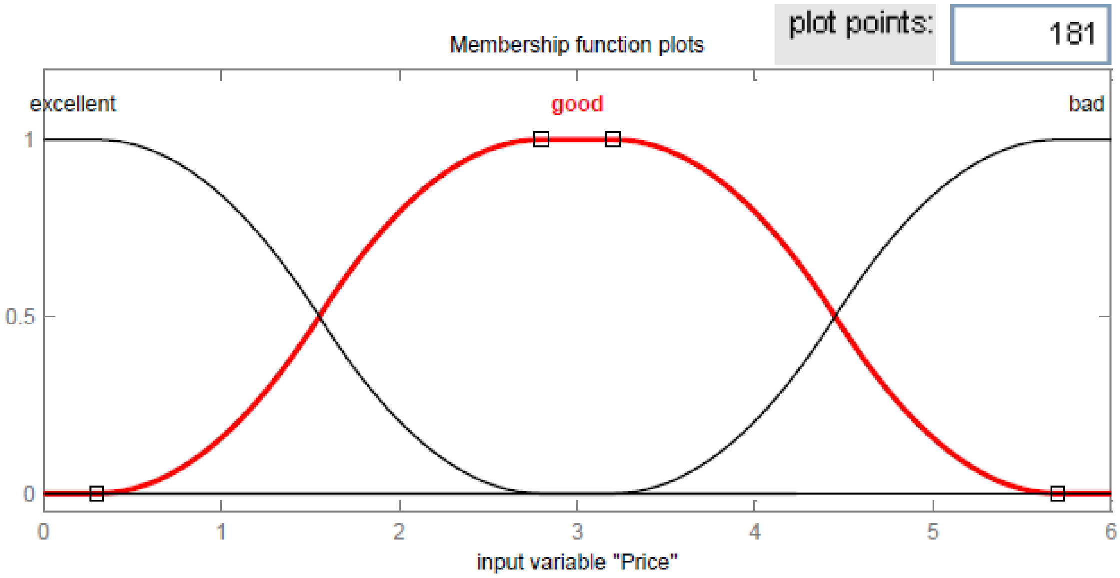


Figure 4.2: Price Membership Function

The “bad”, “good” and “excellent” fuzzy sets shown in Figure 4.2 comprise the membership function selected to assign membership to the price input values in the first pressure vessel material selection. The orientations of these functions were left unchanged from the default selection of three pimf functions. The default selection is symmetrical and the first and third fuzzy sets intersect with the middle fuzzy set at one quarter and three quarters of the input variable's range. The price membership function was left as the default plot due to the inexact nature of the estimated prices and because a symmetrical membership function was desirable in this case.

Figure 4.3 shows the membership function created to assign membership to the corrosion resistance input values in the pressure vessel material selections. This plot is not symmetrical like the membership function shown in Figure 4.2. The pimf functions were assigned in the corrosion resistance membership function so that a PREN value less than 27 will have a majority of membership in the "bad" fuzzy set while a PREN value of more than 50 will have a majority of membership in the "excellent" fuzzy set. The decision to arrange the functions in this way was based on expert knowledge and an estimation of the corrosion resistance required for the pressure vessel to perform adequately in the working environment.

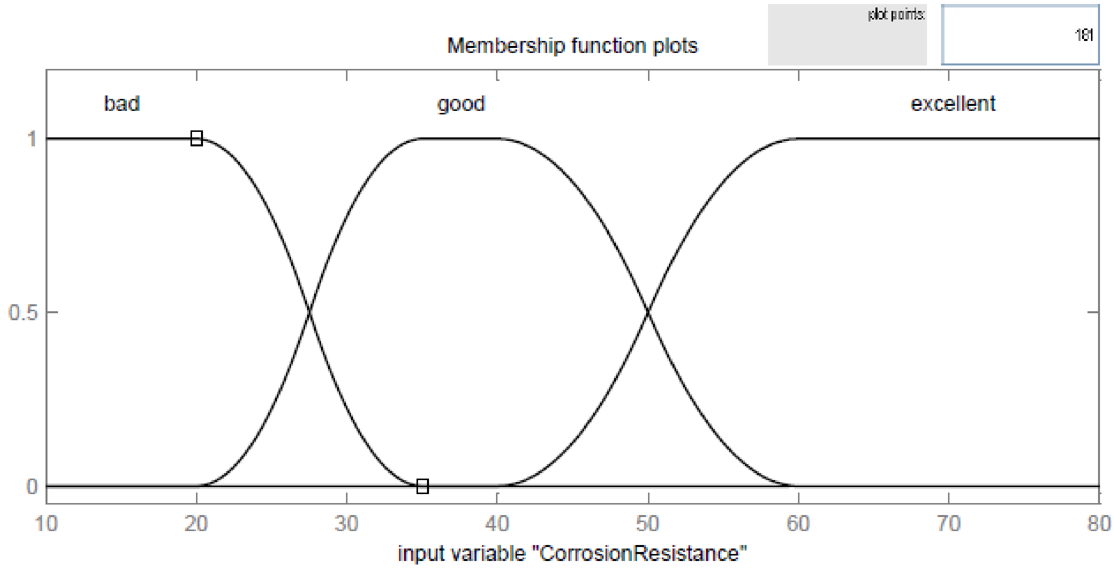


Figure 4.3: Corrosion Resistance Membership Function

Figure 4.4 shows the membership function created to assign membership to the yield strength input values in the pressure vessel material selections. Like the membership function shown in Figure 4.3, the “excellent” range comprises much of the plot while the “bad” range makes of very little of it. The fuzzy sets are arranged in this way to represent the estimated ranges of performance. While some candidate alloys being considered have yield strengths well in excess of 500 MPa, anything in excess of 200 MPa is more than adequate to meet the performance requirements of the pressure vessel. However, a higher yield strength will reduce the wall thickness of the pressure vessel and reduce cost and weight of the system.

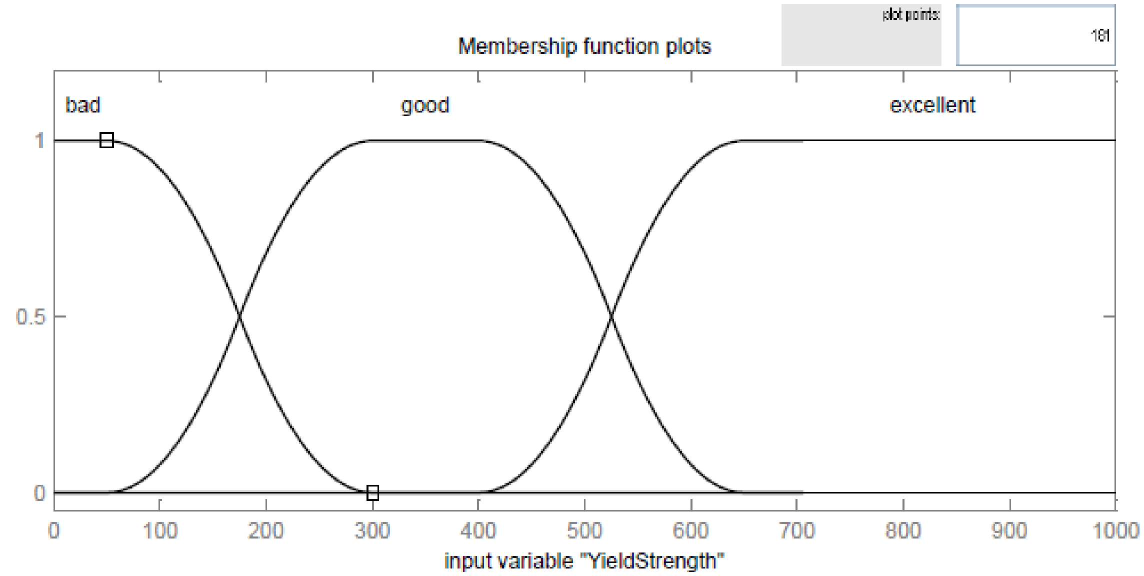


Figure 4.4: Yield Strength Membership Function

Figure 4.5 shows the membership function created to assign membership to the weldability input values in the pressure vessel material selections. Much like the material price membership function, the orientations of these fuzzy sets were left unchanged from the default selection of pimf functions. The weldability membership function was left as the default pimf plot due to the inexact nature of the formulated weldability index and because a symmetrical membership function was desirable. A weldability index of 2 will have equal membership with the “bad” and “good” fuzzy while a weldability index of 4 will have equal membership with the “good” and excellent fuzzy sets.

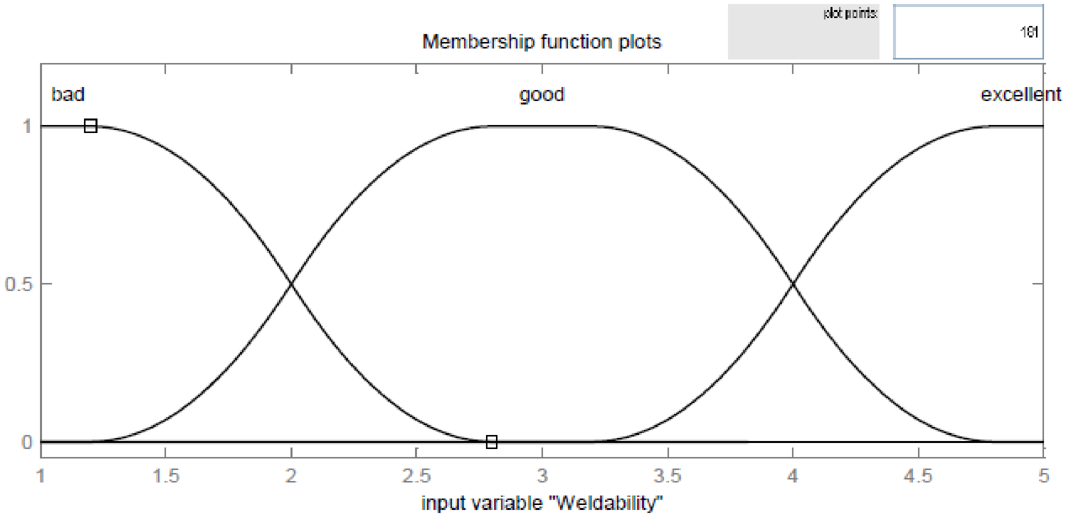


Figure 4.5: Weldability Membership Function

Figure 4.6 displays the membership function created to assign membership to the charpy impact strength input values in the pressure vessel material selections. Again, the orientations of the three fuzzy sets were left unchanged from the default pimf selection. This was done because a large “good” range was desired based on the uncertainty of the estimated required toughness.

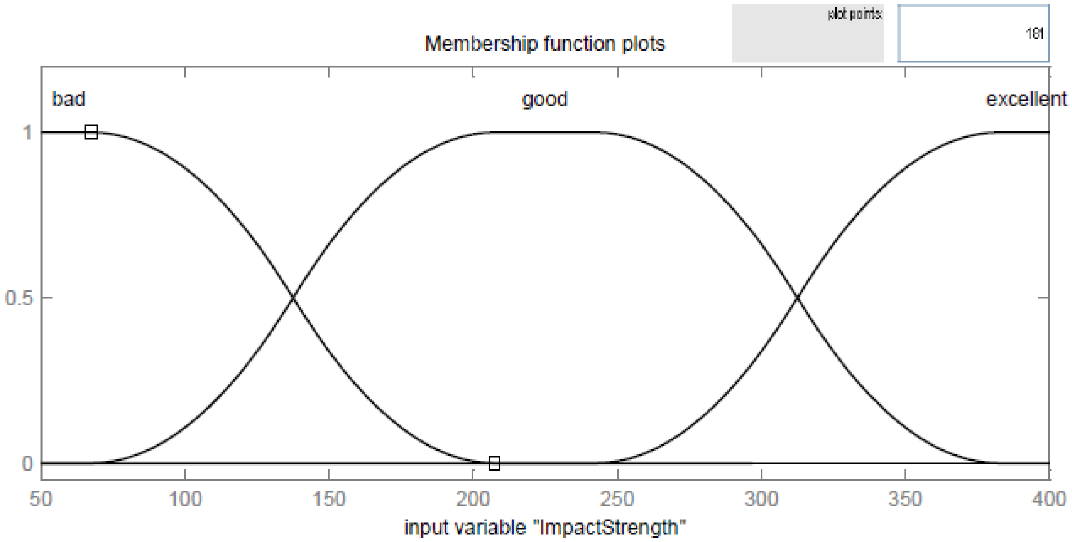


Figure 4.6: Impact Strength Membership Function

Figure 4.7 shows the membership function selected to defuzzify the output, calculated using the simplifying rules, into a performance index. Defuzzification is the process of converting the assigned degrees of membership into an output using the defined simplifying logics. While only three fuzzy sets were used in the input membership functions, five fuzzy sets are employed here. The decision to use more fuzzy sets in the output function than in the input functions is due to the nature of the simplifying rules. Using more than three fuzzy sets would cause an explosion in the number of possible expressions. Reducing these to simplifying rules would be a herculean task. For the current case study 3 fuzzy sets and 5 properties are considered for the input. This results in a possible $3^5 = 243$ expressions. If 5 fuzzy sets were used for the input values instead this would result in $5^5 = 3125$ possible expressions, almost 10 times as many! However, increasing the number of fuzzy sets used in the material performance membership function increases the separation of candidate materials in the output, making it easier to identify performance, but doesn't increase the number of simplifying rules required.

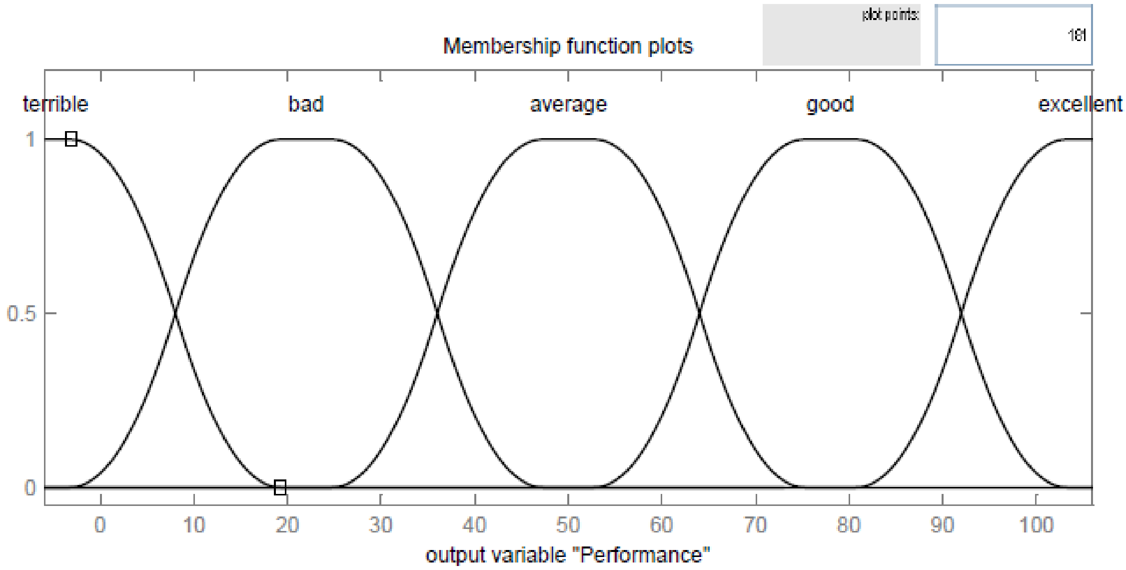


Figure 4.7: Material Performance Membership Function

The five fuzzy sets used in the material performance membership function are "terrible", "bad", "average", "good", and "excellent". Again, the pimf shape is employed to map the fuzzy sets. Notice that the range of output values extends slightly beyond that of the desired 0 to 100 range previously stated. The range of values stipulated for this output functions is -6 to 106, but since the centroid defuzzification method was selected, as shown in Figure 4.7, the actual output will be between 0 and 100. You can see by looking closely at Figure 4.6 that full membership in the terrible and excellent ranges actually occurs right at 0 and 100 respectively. The use of the centroid defuzzification method is recommended as it results in a more smoothly shaped rule surface. In other words, the output performance index is less sensitive to slight variations in input values which occur near the fuzzy set overlaps.

After the input and output membership functions are all defined and their fuzzy sets properly configured, the next step is to write the simplifying rules used to transform the input into output. As shown in the next section, this is the most crucial step in creating a fuzzy logic material selection system.

4.1.3 Simplifying Rules for Pressure Vessel Including Cost

Both the reliability of the fuzzy logic material selection method and the learning curve involved in its use are centered on writing the simplify rules. After much trial and error a systematic method focused on the two most vital material attributes is suggested. To illustrate this method the simplifying rules written for the pressure vessel selection, both with and without price included as an input variable, are presented and analyzed.

In writing the simplifying logics for the first pressure vessel material selection (the one including price), the two most important material attributes to performance were first identified. The identified material properties are price and corrosion resistance. Since there are three fuzzy sets used in the input functions there are nine resulting combinations of membership for the price and corrosion resistance variables. Since there are five material properties being used as inputs for this selection there are a total of 243 possible expressions. This means that for each of the nine combinations of price and corrosion resistance membership there are 27 ways that yield strength, impact strength and weldability can be assigned membership. Figure 4.8 displays each of the nine price and corrosion membership combinations and lists the number of simplifying rules written for each. When the simplifying rules are broken down in this way they also become far easier to formulate and keep track of. The number of rules to be evaluated was drastically reduced from 243 to 43 using this method.

Table 4.1: Simplified Membership Combinations for Pressure Vessel

Price	Corrosion	No. of Possible Expressions	Simplified No. of Expressions
B	B	27	1
B	G	27	2
B	E	27	6
G	B	27	3
G	G	27	10
G	E	27	5
E	B	27	7
E	G	27	8
E	E	27	1
		Total = 243	Total = 43

B = bad, G = good, E = excellent

The criteria for reducing the number of simplifying rules basically amounts to relating the combinations of material property performances to the component's overall performance. This requires a fair amount of expert knowledge of the component and what contributes to its performance in the design environment. In the case of the pressure vessel, if a material has "bad" corrosion resistance (a PREN less than 27 was previously defined as bad) it won't perform well in the working environment. Also if the price of the material is too high the system will be too costly to manufacture and won't be feasible. Using this logic if both the price and the corrosion resistance of a candidate material are "bad", then the performance will be "terrible", no matter what the values of yield strength, impact strength, and weldability are. Notice that each alloy being considered in this case study has a minimum amount of yield strength, impact strength, and weldability to be used as a pressure vessel. That is why they can be ignored in the case that price and corrosion resistance are both in the defined “excellent” ranges. If both the price and corrosion resistance are “excellent”, the performance will be “excellent”, no matter the other input variable’s values. Also, an alloy’s price generally escalates as its corrosion resistance increases, making an alloy that is both inexpensive and highly corrosion resistant extremely rare. Certainly not every material selection should assign a high performance index to a material that performs well in the two most vital membership functions regardless of the other material attributes. Each set of simplifying rules should be written on a case by case basis and should be based upon expertise knowledge.

The simplifying rules written for each case study material selection are displayed in Appendix B in Tables B1 through B5. The rules for the pressure vessel material selection including price are listed in Table B1 in the same format previously described. In the case that price is “bad” and corrosion resistance is “good” two simplifying logics are employed. The first states that if both weldability and toughness (charpy impact strength) are “excellent” then the performance of the component will be “average”. The other rule states that if either weldability or toughness isn’t “excellent” the performance will be “bad”. In both rules the membership of yield strength is ignored. These two simplifying logics cover all 27 possible expressions of the case when price is “bad” and corrosion resistance is “good”.

As shown in Table 4.2, more simplifying rules are generally required when both vital material properties have “good” membership (or any membership that isn’t on the extreme low or high end of performance). This is because the overall performance of the component now relies more heavily on the combination of the other material attributes and because this case results in a greater range of possible output membership. In the pressure vessel material selection, ten simplifying rules have been defined for the situation when price and corrosion resistance are both “good”. Out of these rules only one defines “excellent” performance, three define “good” performance, three define “average” performance and three define “bad” performance. The logic used in these ten rules assigns “average” performance if only one of the remaining three material properties is “bad” and assigns “bad” performance if two or more of the remaining three material properties are “bad”. If none of these three material properties is in the “bad” range the performance will be either “good” or “excellent”. “Excellent” performance is assigned only when both weldability and toughness are “excellent”.

A simple way of reducing the required number of rules is to employ the “all conditions except” definition to the formulation of the rules. In Appendix B a bracketed fuzzy set denotes all conditions except the one in the brackets. In other words, (B) stands for any condition except “bad”. In the case studies presented here, “good” and “excellent” are simultaneously defined by (B). The (B) definition saves time in writing rules to assign membership as it can be used to filter out materials with input values below a defined minimum. As shown in Table B1, the ( ) definition is used in almost half of the simplifying logics written for the pressure vessel material selection.

4.1.4 Simplifying Rules for Pressure Vessel Not Including Cost

The simplifying rules selected for the second pressure vessel material selection, the one not including the price index of the material, were centered on the corrosion resistance and weldability material properties. Because there was one less input variable, the number of simplifying rules required to express performance were fewer. The total number of expressions for this selection is $3^4 = 81$. The simplifying rules for the pressure vessel material selection without cost included were reduced to 34 expressions and are displayed in Table B2.

The first rule listed in Table B2 simplifies two of the nine rule subsets with a single rule. It states that if corrosion resistance is “bad” and weldability is not “excellent” then performance is “terrible”, regardless of yield strength and toughness. Thus if the corrosion resistance of a material is “bad” and the weldability is either “bad” or “good”, the material is assigned “terrible” performance.

Unlike the simplifying rules for the first pressure vessel material selection, this selection defines more than one rule for the case when the two most vital properties are both in the “excellent” range. There are four rules defined; the first states that if both corrosion resistance and weldability are “excellent” and yield strength and toughness are both “not bad” then the pressure vessel’s performance is “excellent”. The second of these rules states that if the yield strength is “not bad” and the toughness is “bad” the performance will be “good”. The third rule states that if the yield strength is “bad” and the toughness is “not bad” performance is “average”. The fourth rule defines performance as “terrible” if both the yield strength and toughness are “bad”. Unlike the previous selection’s simplifying rules, this selection defines four possible performance ranges for cases in which the two main material properties are both “excellent”.

4.1.5 Fuzzy Evaluation Results

This section presents and discusses the results of the material selections for the two pressure vessel cases. It also describes the steps involved in evaluating candidate materials once the membership functions and simplifying rules have been defined. For both the pressure vessel selections all the stainless steel and nickel alloys in the database are evaluated as candidate materials.

A database of candidate material properties should be arranged so that each row corresponds to a candidate material and each column to a material property (See the candidate materials tables in Appendix A). By doing this material data can easily be evaluated and the resulting performance index can be matched to the corresponding material. A group of candidate materials is evaluated by copying the required material properties from the database (in spreadsheet format) and pasting them into the evaluation function in the MATLAB editor. The evaluation function is:

```
fismat = readfis(‘insert file name here’);
out = evalfis([insert candidate materials data here],fismat)
```

The fuzzy logic material selection file name and candidate material properties should be inserted as indicated above in red. When entering the candidate material properties, each column of values correlates to a specific input variable and the columns should match the order that the input variables were defined in. The input variables are defined in top to bottom order, in the FIS window of the Fuzzy Toolbox. In the case of the first pressure vessel selection, the input variables were defined in the following order: 1) Price, 2) Corrosion Resistance, 3) Yield Strength, 4) Weldability, 5) Impact Strength (as shown in Figure 4.1). So each column of values, corresponding to a specific material property, must be entered into the evaluation function in this order.

The output of all the case study material selections is presented in Table B6 of Appendix B. As expected, the performance indices vary considerably between the two pressure vessel material selections. The material selection including price as an input variable shows a much smaller range in candidate material performance. This is largely due to the fact that corrosion resistance and price vary inversely for most alloys. Thus no alloy meets the “excellent” performance criteria of having great price and great corrosion resistance. Likewise, no material performs in the terrible range as an expensive alloy will typically have high strength and corrosion resistance.

The pressure vessel material selection without price shows a much larger range in performance of the materials. Several of the nickel alloys exhibit high performance marks, as do a couple of the austenitic and duplex stainless steels. This is due to the lack of price as an input variable. Without the inclusion of price, a material’s performance is a function only of its mechanical and physical properties. The resulting small range of performance indices and the increased difficulty of selecting good simplifying rules lead to the conclusion that it may not be a good idea to include price as an input variable, at least for the present case study.

Table 4.2: Estimated Price of Alloying Additions

Alloying Addition	Price ($/lbs)
Aluminum	0.70
Chromium	2.00
Cobalt	12.00
Copper	2.00
Iron	0.10
Magnesium	1.75
Manganese	2.25
Molybdenum	8.00
Nickel	5.00
Niobium	20.00
Silicon	1.50
Titanium	3.25
Tungsten	12.00
Zinc	1.00

[42]

But price is an important part of assessing a material for use in any design. Therefore it is suggested that the performance indices of the candidate materials be normalized by the price of the material. The resulting value will indicate how much performance a material delivers per unit cost. In this case study the cost of each material has been estimated by multiplying the percentage of each alloying element addition by that addition's price per pound (according to metalprices.com as of April 15th, 2009). The values used for the prices of the alloying additions are shown in Table 4.3. Although these values don't take into account the costs of treatments and fabrication, they provide a solid foundation for comparing the prices of the candidate alloys.

Table B7 in Appendix B displays the performance indices of all the material selections normalized to the estimated prices of the alloys. While this information has its uses, a final material selection should not be determined using it alone. Notice that the nickel alloys generally perform poorly compared to the other candidate alloys. This is because the nickel alloys are the most expensive of the candidate alloys. Their use should be reserved for situations when their extra cost can be justified by their superior performance. Furthermore, the higher strength alloys can often be used to reduce the required weight of a component. This reduces the cost of the component and makes up for some of the price difference between a more and less expensive material. Table B7 should be used to compare the cost effectiveness of materials of similar classification.

4.2 Material Selection for Turbine Blades

4.2.1 Material Attributes Vital to Performance

The function of the turbine blades in the kinetic energy conversion system is to convert the linear momentum of the Gulf Stream current into rotational motion that can then be transformed into electrical energy by the generator housed within. Like the pressure vessel, the turbine blades will constantly experience dynamic loadings. Therefore, yield strength and toughness (expressed as charpy impact strength) have been chosen as two of the fuzzy selection material properties.

Like the pressure vessel, the turbines blades must be resistant to corrosion, both localized and uniform. In order to achieve variety in the material selections, it is assumed that the turbine blade would have an organic, corrosion resistant coating, if it was made out of an alloy. This assumption allows much of the focus to be taken off of corrosion resistance and transferred to the other material attributes. This also allows the addition of aluminum alloys to be evaluated as candidate materials, which normally wouldn’t have the corrosion resistance required. An artificial PREN value of 20 was assigned to all candidate aluminum alloys in this study so that their corrosion resistance could be compared to that of the stainless steel and nickel alloys.

Corrosion resistance is still important as organic coatings inevitably contain imperfections and suffer damage over time (wear of physical damage) so that the underlying substrate is exposed to the corrosive working environment. By removing a large amount of emphasis off of corrosion resistance the turbine blade selection now becomes quite different from the pressure vessel selection. This adds variety to the case study material selections and enables the validity of the fuzzy logic material selection process to be examined in a different perspective.

Machinability and weldability are both important attributes to be considered when selecting an alloy for the turbine blades. However, only weldability was chosen as a material property for this selection. Weldability is the better defined index of the two and shows greater variability from alloy to alloy. This variability will lead to more scatter in the resulting performance indices and allow an easier assessment of the simplifying rules.

The final material property chosen for the turbine blade selection is density. A low density is extremely vital to the performance and efficiency of the system. The lighter the turbine blades are the more easily they will be rotated by the flowing water, thus potentially increasing the generated power.

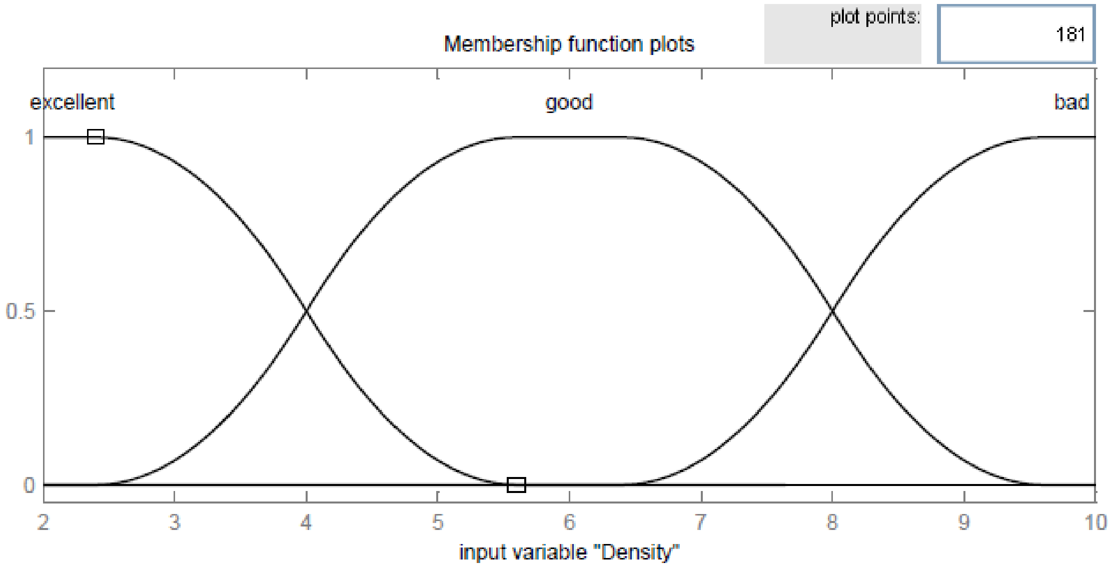


Figure 4.8: Density Membership Function

The membership functions used in the turbine blades selection are identical to those used in the pressure vessel selection for the corrosion resistance, yield strength, weldability and impact strength material properties. For the additional membership function of density, the default symmetrical pimf plot was used. The range of values was set as 2 to 10 grams/cm^3. Unlike the other membership functions, a lower value of density is desirable. Therefore, the "excellent" fuzzy set was defined for the lower range of values, with the transition between "excellent" and "good" occurring at 4. The "bad" fuzzy set was defined for the higher range of values with the transition between "bad" and good occurring at 8. Figure 4.8 shows the membership function created to assign membership to the density input values in the turbine blades material selection.

4.2.2 Simplifying Rules and Evaluation

The simplifying rules selected for the turbine blades material selection were centered on the density and weldability material properties. The remaining material properties, strength, corrosion resistance, and impact strength, were considered to be equally important to performance. The created simplifying rules are listed in Table B3 of the Appendix.

Since five membership functions are employed, there exists a total of $3^5 = 243$ expressions to assign performance to. The first rule listed in Table B6 accounts for a third of these expressions. It states that if density is “bad” performance is “terrible”. From this point six combinations of the two vital membership functions remain. For these six combinations four scenarios were identified to base the simplifying rules on. For each of the less vital material properties, 1) all could be “not bad”, 2) any one of the three could be “bad” while the other two are “not bad”, 3) any two of the three could be “bad while the other two are “not bad”, or 4) all three could be bad. Each of these four situations was used to write rules for the six remaining combination of membership for density and weldability. In all 45 simplifying rules were employed.

The output from the material selection for the turbine blades is displayed in Table B6. Out of all the selections it showed the smallest range between the highest and lowest assigned performance indices. However, this can be attributed to the candidate alloys and not a weakness in the simplifying rules as no candidate alloy had a low density, adequate corrosion resistance and adequate impact strength to achieve more than “average” performance. As indicated earlier other candidate materials (e.g. composites) could be added to the database, if all parameters are identified.

4.3 Material Selection for Drive Shaft

4.3.1 Material Attributes Vital to Performance

The function of the drive shaft in the kinetic energy conversion system is to transfer the rotational motion achieved by the turbine blades to the generator so that the conversion into electrical energy can be made. Four material attributes were identified as being important to the successful performance of this task. They include yield strength, impact strength, machinability and hardness.

Based on the calculated loadings the drive shaft for the pilot project requires a minimum yield strength of 150 MPa. The yield strength membership function was created so that anything below a value of 150 MPa will have a majority of membership in the “bad” fuzzy set. In this way a simplifying rule can be written that will eliminate all candidate materials that have a yield strength below this point.

The drive shaft will have a long service life and will constantly experience a torsional loading while the system is operating. Toughness, expressed as yield strength, is an important material property for withstanding the resulting fatigue. The same impact strength membership function that was used for the pressure vessel and turbine blades is employed for this case.

Machinability is an important material property in this selection because due to the required thickness of the drive shaft. An easily machined material will cut down on the cost and time of fabrication of the drive shaft. Machinability is an input variable that hasn’t been used in either of the preceding case study material selections. An index denoting how easily an alloy can be machined was assigned to all candidate alloys using a scale of 1 to 5 in the same way the weldability index was assigned. A score of 1 denotes very bad machinability while a 5 denotes excellent machinability. Thus, the membership function used to assign membership to the machinability input values is identical to the weldability membership function.

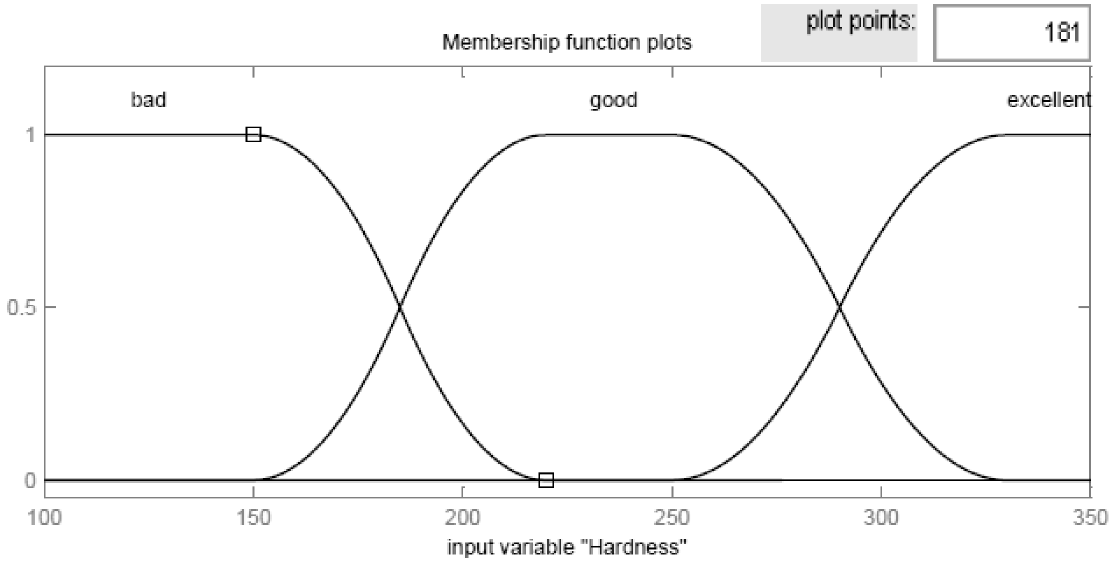


Figure 4.9: Hardness Membership Function for Drive Shaft

Hardness is another input variable that hasn’t been utilized in the preceding selections. For ease of comparison the hardness of all the candidate alloys were converted to the Brinell Hardness Index. Hardness is an important material attribute for this material selection because the surface of the drive shaft must remain smooth and damage free in order for it to function properly. As shown in Figure 4.10, the membership function was defined so that a hardness value less than 180 will have a majority of membership in the “bad” fuzzy set while a hardness value greater than 290 will have a majority of membership in the “excellent” fuzzy set.

4.3.2 Simplifying Rules and Evaluation

The simplifying rules selected for the drive shaft are centered on the yield strength and hardness material properties. The machinability input variable was identified as the third most important to performance and the impact strength as the least important. The created simplifying rules are listed in Table B4 of the Appendix.

Since four membership functions are employed, there exists a total of $3^4 = 81$ expressions to assign performance to. The last two rules listed in Table B4 account for a third of these expressions. They state that if either the yield strength or hardness of a material are “bad” then its performance is “terrible”. In total 26 simplifying rules were utilized, written using the same method of focusing on the two most vital material attributes as the preceding cases. Notice that because impact strength is the least vital attribute to performance, most of the rules include it as either “bad” or “not bad” to help separate between adjacent performance indices.

4.4 Material Selection for Mooring Connection

4.4.1 Material Attributes Vital to Performance

The function of the mooring connections in the kinetic energy conversion system is to provide a tie-off point for the mooring lines which hold the system in place. These connection points will be directly attached to the system and will see significant amounts of loading. Because of the dynamic nature of the loadings, wear caused by rubbing action from at the connection points could be a major problem. Because of this yield strength, impact strength and hardness have been identified as important material attributes contributing to the performance of this component. The same impact strength membership function used in the previous cases is again employed here. The yield strength membership function employed is identical to the ones used in the pressure vessel and turbine blades cases. The hardness membership function uses the default pimf fuzzy sets distributed over a range from 100 to 350 on the Brinell Hardness Index. The hardness membership function is displayed in Figure 4.11.

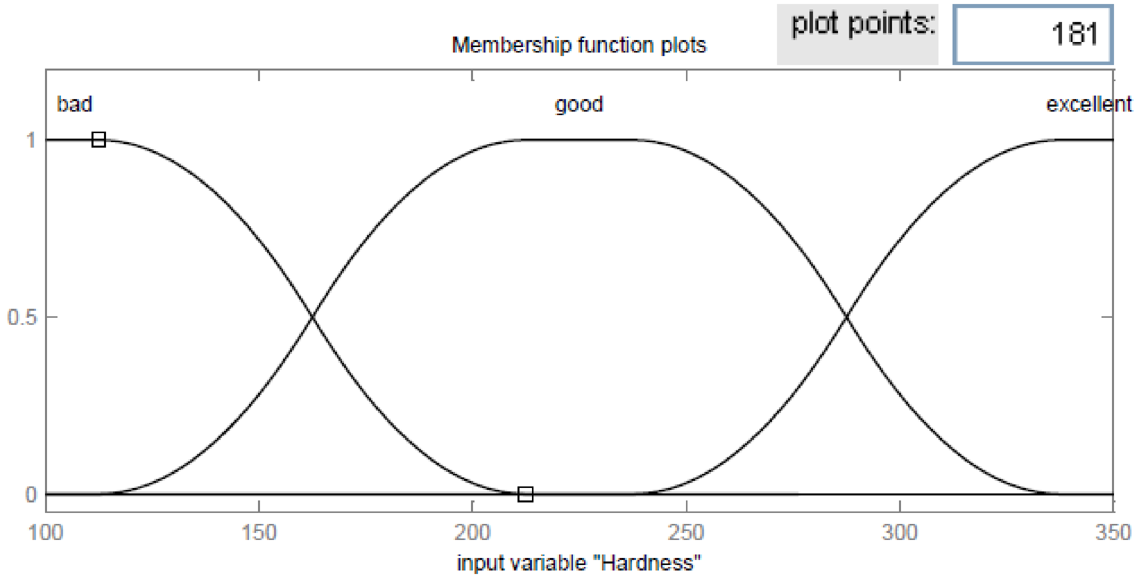


Figure 4.10: Hardness Membership Function for Mooring Connection

The other two material attributes identified as relevant to the material selection are corrosion resistance and weldability. Like all components exposed to the sea the ability to resist any and all forms of corrosion is necessary to meet service life requirements and avoid catastrophic failure. Weldability will be of major importance because the ocean energy system connection components will likely be made of slender alloy members welded together. The membership functions for both corrosion resistance and weldability remain unchanged from the previous case studies.

4.4.2 Simplifying Rules and Evaluation

The simplifying rules written for the mooring connections are centered on the corrosion resistance and impact strength material properties. Yield strength was also identified as vital and any material candidate that is assigned “bad” membership for yield strength will automatically receive “terrible” performance. The remaining simplifying rules require that yield strength be “not bad”. The rules were written in the same style as in the preceding cases by grouping them into the nine combinations of the two most vital properties, and then considering how the combinations of the other properties would impact performance. In this case hardness and weldability were considered of equal importance in all the rules. In all 43 simplifying rules were employed and they cab be found in Table B5 of the Appendix.

5 Validation of Fuzzy Logic Approach by Comparison

5.1 Method of Comparison

In order to analyze the results of the fuzzy logic material selections a second material selection has been performed for each of the previously considered components using a simple, proven, and reliable method. In this approach each material attribute is assigned a weighting factor corresponding to its relative importance in the material selection. These weighting factors are derived using the digital logic method [31]. Using this method each material attribute is compared to every other material attribute one-on-one. If an attribute is less vital to the selection than the one it is being compared to it receives a score of 0, if it is equally important it receives a 1, if it is moderately more important it receives a 2, and if it is much more important it receives a 3. A table is organized so that each material attribute is listed in successive rows and then again in successive columns, forming an NxN matrix. Using this format each row, denoting a material property, is compared to every material property in the columns to the right using the described method. The sum of each row is then calculated in a column to the right of the NxN matrix. A total sum of all numeric decisions assigned is then formulated. The weighting factor for each material is then found by dividing the sum of each row's numerical decisions by the total sum of numerical decisions. Tables C1 through C5 in the

Appendix display the decision matrices used to calculate weighting factors for each of the case studies. The numerical decision assigned to each material comparison corresponds to the importance previously determined for each component in the last chapter. In this way an accurate comparison can be made between the two material selection techniques.

Once the weighting factors are determined assigning performance indices to each material is a simple task. In order to assign a performance index to a material based on the determined weighting factors the material properties must first be normalized. One property is considered at a time and is scaled so that the highest numerical value does not exceed 100. The best value among the candidate materials is rated as 100 and the others are scaled proportionally. By introducing a scaling factor normal material property values are converted to dimensionless values. For material properties in which higher values are more desirable the scaled property is found by dividing the numerical value of the property by the maximum value on the list and multiplying by 100. For material properties in which lower values are more desirable the scaled property is found by dividing the maximum value on the list by the property value of the material being considered and multiplying by 100. Tables C6 through C10 in Appendix C display the calculation of the weighted performance indices for each of the case studies.

5.2 Comparing the Results of the Material Selections

One way to determine the validity of a material selection is to examine the distribution of its results. A large distribution in the performance assigned to the candidate materials typically denotes a quality selection. Tables 5.1 and 5.2 display the maximum and minimum resulting performance indices assigned for each material selection by both the fuzzy logic method and the weighted properties method. These tables also show the average performance indices assigned and the difference between the maximum and minimum performance indices.

Table 5.1: Comparison of Results for Fuzzy Logic Method

Performance Index	PV w/ cost	PV w/o cost	Turbine Blades	Drive Shaft	Mooring Connection
Max	86.9	98.6	55.6	63.8	96.2
Min	21.3	1.4	10.6	1.4	2.2
Average	57.1	52.0	33.3	33.5	47.4
Max - Min	65.6	97.1	45.0	62.3	94.0

Table 5.2: Comparison of Results for Weighted Properties Method

Performance Index	PV w/ cost	PV w/o cost	Turbine Blades	Drive Shaft	Mooring Connection
Max	62.1	90.6	72.1	76.3	83.6
Min	37.0	29.8	27.5	41.4	30.4
Average	51.8	54.3	53.6	51.5	49.4
Max - Min	25.1	60.8	44.6	34.9	53.2

Note that the difference between the maximum and minimum assigned performance index is larger in every case for the fuzzy logic method. In fact, it is about twice as large for each case except the turbine blades. Also notice how the average performance value assigned is almost exactly half way between the minimum and maximum values for all the fuzzy logic selections. This is another indicator of an even and balanced distribution in the results. This isn't always the case in the weighted properties selections. For all the selections, with the exception of the turbine blades, using the weighted properties method, the average performance is much closer to the minimum than the maximum. The fact that the fuzzy logic method shows a much larger and more even distribution in the assigned performance indices when compared to another proven and reliable method is a strong indicator of its validity.

A major concern is whether or not the fuzzy logic method is able to accurately pick the higher and lower performing materials for a component. In other words the materials you would want to use and the materials you would want to avoid. This is a tough question to answer, and much of the strength of the fuzzy logic method depends upon the user to accurately describe the requirements of a component using the simplifying rules.

In the pressure vessel material selection not including price duplex alloys Zeron 100 and SAF 2507 were identified as the highest performers, each with a performance index of 86.86. In the corresponding weighted properties selection these were the 5th and 6th highest performing alloys with scores of 58.2 for SAF 2507 and 58.6 for Zeron 100. Alloy 686 was the highest performer with a performance index of 62.1. However, it is interesting to note that the 2nd, 3rd, and 4th highest performing alloys in the weighted properties selection were all duplex stainless steels. So while the two method don't agree on the top overall material for the job, they do agree that duplex stainless steels would work very well. This is a very encouraging development for the unproven fuzzy logic method.

In this same material selection the ferritic stainless steels were identified as the worst performing materials by the fuzzy logic method. All but one of them received a performance index below 30. This was not the case for the weighted properties method as the Monel alloys were identified as the worst performing materials. The ferritic stainless steels received marks a little below the average. This doesn’t mean that the fuzzy logic method was incorrect; in fact it seems more likely that the fuzzy logic method got it right based on the results thus far. Looking at the results of the weighted properties method reveals that few of the assigned performance indices deviate very far from the average value. This makes it extremely hard to deduce what truly are the best and worst performing materials for a design.

The results of the material selections are in even more agreement for the case of the pressure vessel not including price. In the fuzzy logic selection nickel alloys 686 and C-276 were identified as the highest performing materials. The same was true for the weighted properties method except in the reverse order. The worst alloy according to the fuzzy logic method was ferritic stainless steel alloy 430. This was the second lowest performing material in the weighted properties method.

The remaining three cases show similar results with the best and worst performing alloys in close agreement between the two methods more often than not. This provides a large amount of evidence towards the validity of the fuzzy logic method. It is becoming clear that the fuzzy logic method of material selection can be a useful tool in selecting materials for renewable ocean energy applications.

6 Discussion: Implementation of Fuzzy Logic

The use of fuzzy logic to aid in process and materials selection is a recent addition to the wide range of tools available to the materials engineer. It is rapidly gaining in momentum as a variety of applications have been identified that can benefit from its implementation. A similar approach to the one presented in this thesis was used to demonstrate fuzzy logic's ability to perform materials selections through the case study selections of a liquid nitrogen storage tank, the spar of an aircraft wing, and a hollow cylinder mast for a sailing boat [42]. Fuzzy Logic has been implemented to select proper coatings to resist both corrosion and wear [44]. It has also proved to be useful in selecting the best silicon wafer slicing technology [45].

Throughout the publications on fuzzy logic based materials selections there are a wide variety of methods employed to accomplish the material selections. This is due to an inherent quality in the framework of fuzzy logic. The "fuzziness" of fuzzy logic leaves it open to human interpretation. Two experts using this thesis' fuzzy logic method for the same material selection will come up with differently shaped membership functions and different simplifying rules. If the two experts have a strong knowledge of the design component and what is required of it in the intended application, then these differences should be slight and the variations in the candidate materials assigned performance indices will be minimal. The innate inexactness of fuzzy logic is a strength, not a weakness. If the defined fuzzy logic system accurately describes the requirements of a component and defines the possible ranges of performance using the membership functions and simplifying logics, then the results should be reliable.

This isn’t to imply that there isn’t a proper way to implement the fuzzy logic system presented here, because there most certainly is. Unlike some other fuzzy logic material selection methods, the method presented here works best if the defined fuzzy sets have significant regions of full membership so that they are plateaued at the top and thus shaped in a trapezoidal manner. This need is based on the presented method recommending only three input fuzzy sets for simplicity. The slopes of the fuzzy sets in the membership functions need to remain sharp so that there isn’t too much overlap amongst them. Too much overlap would result in a high percentage of the input values fitting in between the simplifying logics and this would reduce the range and even distribution of the output indices.

Care should also be taken to avoid oversimplification of the reducing logics as this can lead to a lack of separation in the assigned performance indices. This lack of separation makes it impossible to distinguish the adequacy of one material from another. Oversimplification of the rules can also cause materials to be assigned misleading or incorrect performance indices [42].

Any material selection performed with corrosion resistance as a major consideration faces a substantial challenge. The difficulty is that there is a lack of quantitative information available to compare and assess materials for use in a corrosive environment. The method suggested here is comparison based on PREN alone. While this provides a fairly reliable index for assessing localized corrosion resistance, it only applies to stainless steels and nickel based alloys. Coming up with quantitative information to compare the corrosion resistances of dissimilar alloys is exceedingly difficult. Trying to compare the corrosion resistance of a metal to a non-metal is next to impossible. Therefore it is extremely important to employ supporting information to reevaluate the top performing materials from the fuzzy logic selection to more accurately predict how they will perform in the specific working environment, coupled to the other materials in the system.

The recommendations presented in this thesis, to aid in the creation of the membership functions and writing of the simplifying rules will enable the user to overcome much of the uncertainty inherent to fuzzy logic and perform accurate and reliable material selections.

7 Conclusions

Based on the results of the literature review and material selections it is apparent that the presented fuzzy logic method can provide reliable material selections for renewable energy applications. Results obtained using the fuzzy logic method show a much larger and more even distribution in the assigned performance indices when compared to those of the digital logic method. The fuzzy logic method is easy to implement and can simultaneously deal with quantitative and qualitative properties of materials. Unlike other material selection techniques, there is no need to scale material properties as the simplifying rules take into consideration their relative importance.

The fuzzy logic material selection method's value will be maximized in situations involving new applications or new technologies in which a large number and variety of materials are being considered. This is because the fuzzy logic method can compare both similar and dissimilar materials with a fairly high precession of accuracy. In this way preliminary selections can be made for components in which the designer has very little idea about what the end result will be.

The drawback of the fuzzy logic material selection method is that it requires some getting used to. The majority of the learning curve comes from writing the simplifying rules which describe performance. A strong understanding of the requirements of the component in the design is necessary in order to define adequate rules. At first, this will be a time consuming task. However, once the user has some practice, and begins to use the method suggested for writing rules based on the two most vital attributes, this becomes a far easier and quicker process.

The presented fuzzy logic method, like any other material selection method, shouldn’t be used to make final material selections solely based on the assigned performance indices. Rather it identifies high performing materials that the user can then further research to ultimately make the best selection. A final material selection must be one that is compatible in the system and the working environment.

Appendix A

Candidate Alloys Database

The tables presented in Appendix A are comprised of information gathered from the ASM Handbooks Vol. 1 and 2, the Nickel Development Institute, Special Metals Group, Allegheny Ludlum, and metalprices.com [12, 46, 47, 48, 49, 50].

Table A1: Material Properties of Candidate Austenitic Stainless Steel

Designation		Properties					
Industry	UNS	Fy (MPa)	Ft (MPa)	Young's Modulus	Density (g/cm3)	CTE (µm/m•ºC)	ThrmCond (W/m•K)
304	S30400	205	515	193	8.00	17.2	16.2
316	S31600	205	515	193	8.00	15.9	16.2
316L	S31603	170	450	193	8.00	16.0	16.2
317L	S31703	240	585	200	8.00	16.5	14.4
317LM	S31725	205	515	200	8.00	17.5	16.2
254 SMO	S31254	300	650	200	8.00	16.0	13.0
AL-6XN	N08367	365	690	200	8.06	15.3	11.8
Alloy 825	N08825	300	690	206	8.13	13.9	11.1
904L	N08904	270	605	196	7.95	15.3	11.5
1925hMo	N08926	300	650	193	8.10	16.1	12.0

Designation		Properties					
Industry	UNS	PREN	Impact Strength	Brinell Hardness	Machin-ability	Weld-ability	Estimated $ per lbs
304	S30400	19	200	192	3	4	0.98
316	S31600	25	195	207	3	4	1.29
316L	S31603	25	195	207	3	4	1.29
317L	S31703	30	195	183	3	4	1.46
317LM	S31725	34	195	183	3	4	1.65
254 SMO	S31254	43	110	207	3	4	1.96
AL-6XN	N08367	48	190	207	3	5	2.35
Alloy 825	N08825	32	110	163	3	5	2.59
904L	N08904	36	190	146	3	5	2.23
1925hMo	N08926	42	150	163	3	4	2.32

Table A2: Material Properties of Candidate Duplex Stainless Steel

Designation		Properties					
UNS	Industry	Fy (MPa)	Ft (MPa)	Young's Modulus	Density (g/cm3)	CTE (µm/m•ºC)	ThrmCond (W/m•K)
S31803	2205	450	620	200	7.82	16.5	14.6
S32304	2304	400	600	200	7.80	13.0	18.0
S32550	Ferralium 255	550	760	210	7.81	11.9	14.2
S32750	SAF 2507	550	760	200	7.80	13.1	14.0
S32760	Zeron 100	550	750	190	7.84	12.8	12.9
S32950	7-Mo PLUS	480	690	200	7.74	11.5	15.3

Designation		Properties					
UNS	Industry	PREN	Impact Strength	Brinell Hardness	Machin-ability	Weld-ability	Estimated $ per lbs
S31803	2205	36	250	269	2	3	1.10
S32304	2304	24	117	285	2	3	0.89
S32550	Ferralium 255	39	190	277	2	3	1.22
S32750	SAF 2507	41	220	310	2	3	1.30
S32760	Zeron 100	40	225	270	2	3	1.27
S32950	7-Mo PLUS	37	157	277	2	3	1.06

Table A3: Material Properties of Candidate Ferritic Stainless Steel

Designation		Properties					
UNS	Industry	Fy (MPa)	Ft (MPa)	Young's Modulus	Density (g/cm3)	CTE (µm/m•ºC)	ThrmCond (W/m•K)
S43000	430	205	415	200	7.80	10.4	26.1
S44627	E-Brite	275	450	200	7.66	9.9	16.7
S44635	Monit	515	620	200	7.80	~10	~16
S44660	Sea-Cure	450	585	214	7.70	9.5	16.4
S44735	29-4C	415	550	200	7.67	9.2	15.2
S44800	29-4-2	415	550	200	7.70	9.2	15.1

Designation		Properties					
UNS	Industry	PREN	Impact Strength	Brinell Hardness	Machin-ability	Weld-ability	Estimated $ per lbs
S43000	430	17	217	174	3	2	0.81
S44627	E-Brite	30	75	183	3	1	0.95
S44635	Monit	43	70	183	3	1	1.15
S44660	Sea-Cure	39	70	241	3	1	1.06
S44735	29-4C	43	70	207	3	1	1.06
S44800	29-4-2	42	70	207	3	1	1.10

Table A4: Material Properties of Candidate Aluminum Alloys

Designation		Properties				
UNS	Industry	Fy (MPa)	Ft (MPa)	Young's Modulus	Density (g/cm3)	CTE (µm/m•ºC)
A92014	2014 O	97	186	72	2.80	22.5
A93003	Alcad 3003 H14	110	150	70	2.73	23.2
A93004	3004 H32	170	215	70	2.72	23.2
A94043	4043 H16	180	205	70	2.68	22.0
A95052	5052 H34	214	262	69	2.68	23.2
A95083	5083 O	145	290	70	2.66	24.2
A95086	5086 H34	255	325	71	2.66	13.2
A96061	6061 T6	276	310	69	2.70	23.6
A96063	6063 T4	90	172	68	2.69	23.4
A97072	7072	97	131	68	2.72	23.6
A97075	7075 O	103	228	71	2.80	23.4

Designation		Properties			
UNS	Industry	ThrmCond (W/m•K)	Impact Strength	Weld-ability	Estimated $ per lbs
A92014	2014 O	192	25	5	0.83
A93003	Alcad 3003 H14	159	20	5	0.74
A93004	3004 H32	162	25	5	0.78
A94043	4043 H16	~150	15	5	0.81
A95052	5052 H34	~150	25	5	0.81
A95083	5083 O	120	30	5	0.90
A95086	5086 H34	127	22	5	0.88
A96061	6061 T6	180	24	5	0.76
A96063	6063 T4	205	27	5	0.74
A97072	7072	227	20	5	0.75
A97075	7075 O	130	30	5	1.07

Table A5: Material Properties of Candidate Nickel Alloys

Designation		Properties					
UNS	Industry	Fy (MPa)	Ft (MPa)	Young's Modulus	Density (g/cm3)	CTE (µm/m•ºC)	ThrmCond (W/m•K)
N04400	Monel 400	240	550	180	8.80	13.9	21.8
N04405	Monel R-405	240	550	180	8.80	13.7	21.8
N05500	Monel K-500	790	1100	180	8.44	13.7	17.5
N06022	C-22	370	715	205	8.69	12.4	10.1
N06030	G-30	310	690	199	8.22	12.8	10.2
N06059	Alloy 59	380	770	210	8.60	12.2	10.4
N06200	C-2000	110	750	206	8.50	12.4	10.8
N06625	Alloy 625	517	930	207	8.44	12.8	9.8
N07718	Alloy 718	1000	1240	211	8.19	13.0	11.4
N09925	Alloy 925	815	1210	199	8.14	13.2	11.2
N06686	Alloy 686	700	940	207	8.73	12.0	~10
N010276	C-276	355	790	205	8.89	11.2	9.8
R20033	Alloy 33	380	720	195	7.90	15.3	13.4

Designation		Properties					
UNS	Industry	PREN	Impact Strength	Brinell Hardness	Machin-ability	Weld-ability	Estimated $ per lbs
N04400	Monel 400	30	270	130	4	3	3.94
N04405	Monel R-405	30	253	125	4	3	3.94
N05500	Monel K-500	35	100	300	2	4	4.06
N06022	C-22	48	350	209	3	4	5.10
N06030	G-30	47	350	143	4	4	4.20
N06059	Alloy 59	76	300	326	2	4	4.69
N06200	C-2000	76	357	163	3	4	4.73
N06625	Alloy 625	52	133	190	3	4	4.62
N07718	Alloy 718	33	110	331	2	4	3.39
N09925	Alloy 925	34	100	336	2	5	3.33
N06686	Alloy 686	74	400	183	3	4	4.93
N010276	C-276	69	337	183	3	5	5.52
R20033	Alloy 33	38	300	240	3	5	2.45

Table A6: Material Properties of Candidate Copper Alloys

Designation		Mechanical Properties						
UNS	Industry	Fy (MPa)	Ft (MPa)	Elong %	Density (g/cm3)	CTE (µm/m•ºC)	ThrmCon (W/m•K)	Impact Strng
C61400	Al Bronze	310	535	40	7.89	16.2	56.5	81
C63000	NiAl Bronze	407	776	59	7.58	16.2	37.7	18
C70600	90-10 CuproNi	338	415	20	8.94	17.1	40.0	60
C71500	70-30 CuproNi	140	380	45	8.94	16.2	29.0	107
C72200	CuproNi w/ Cr	125	315	46	8.94	15.8	34.5	80
C83600	85-5-5-5	117	255	30	8.83	18.0	72.0	14
C86500	Mn Bronze	195	490	30	8.30	20.3	87.0	42
C95500	Al Bronze 9D	275	620	6	7.53	16.2	42.0	14
C95700	MnAl Bronze	275	620	20	7.53	17.6	12.1	40
C95800	Alpha NiAl Bronze	240	585	15	7.64	16.2	36.0	22
C96200	90 Cu-10 Ni	172	310	20	8.94	16.2	45.0	135
C96400	70-30 CuNi	255	470	28	8.94	16.0	29.0	105

Table A7: Composition of Candidate Austenitic Stainless Steels

Designation		Composition					
UNS	Industry	C%	Cr%	Cu%	Fe%	Mn%	Mo%
S30400	304	0.08 max	18.0 - 20.0	-	balance	2.0 max	-
S31600	316	0.08 max	16.0 - 18.0	-	balance	2.0 max	2.0 - 3.0
S31603	316L	0.03 max	16.0 - 18.0	-	balance	2.0 max	2.0 - 3.0
S31703	317L	0.03 max	18.0 - 20.0	-	balance	2.0 max	3.0 - 4.0
S31725	317LM	0.03 max	18.0 - 20.0	0.75 max	balance	2.0 max	4.0 - 5.0
S31254	254 SMO	0.02 max	19.5 - 20.5	0.50 - 1.0	balance	1.0 max	6.0 - 6.5
N08367	AL-6XN	0.03 max	20.0 - 22.0	0.75 max	balance	2.0 max	6.0 - 7.0
N08825	Alloy 825	0.05 max	19.5 - 23.5	1.5 - 3.0	22.0 min	1.0 max	2.5 - 3.5
N08904	904L	0.02 max	19.0 - 23.0	1.5 max	balance	2.0 max	4.0 - 5.0
N08926	1925hMo	0.02 max	20.0 - 21.0	0.8 - 1.0	0.40 max	1.0 max	6.0 - 6.8

Designation		Composition					
UNS	Industry	N%	Ni%	P%	S%	Si%	% Other
S30400	304	0.10 max	8.0 - 10.5	0.05 max	0.03 max	1.0 max	-
S31600	316	0.10 max	10.0 - 14.0	0.05 max	0.03 max	1.0 max	-
S31603	316L	0.10 max	10.0 - 14.0	0.05 max	0.03 max	1.0 max	-
S31703	317L	0.10 max	11.0 - 15.0	0.05 max	0.03 max	1.0 max	-
S31725	317LM	0.10 max	13.0 - 17.0	0.05 max	0.03 max	0.75 max	-
S31254	254 SMO	0.18 - 0.22	17.5 - 18.5	0.03 max	0.01 max	0.8 max	-
N08367	AL-6XN	0.18 - 0.25	23.5 - 25.5	0.04 max	0.03 max	1.0 max	-
N08825	Alloy 825	-	balance	-	0.03 max	0.50 max	Al 0.2 max
N08904	904L	-	23.0 - 28.0	0.05 max	0.04 max	1.0 max	-
N08926	1925hMo	0.18 - 0.20	balance	0.03 max	0.01 max	0.50 max	-

Table A8: Composition of Candidate Duplex Stainless Steels

Designation		Composition					
UNS	Industry	C%	Cr%	Cu%	Fe%	Mn%	Mo%
S31803	2205	0.03 max	21.0 - 23.0	-	balance	2.0 max	2.5 - 3.5
S32304	2304	0.03 max	21.5 - 24.5	0.05 - 3.0	balance	2.5 max	0.05 - 0.6
S32550	Ferralium 255	0.04 max	24.0 - 27.0	1.5 - 2.5	balance	1.5 max	2.9 - 3.9
S32750	SAF 2507	0.03 max	24.0 - 26.0	-	balance	1.2 max	3.0 - 5.0
S32760	Zeron 100	0.03 max	24.0 - 26.0	0.5 - 1.0	balance	1.0 max	3.0 - 4.0
S32950	7-Mo PLUS	0.03 max	26.0 - 29.0	-	balance	2.0 max	1.0 - 2.5

Designation		Composition					
UNS	Industry	N%	Ni%	P%	S%	Si%	% Other
S31803	2205	0.08 - 0.20	4.5 - 6.5	0.03 max	0.02 max	1.0 max	-
S32304	2304	0.05 - 0.20	3.0 - 5.5	0.04 max	0.03 max	1.0 max	-
S32550	Ferralium 255	0.10 - 0.25	4.5 - 6.5	0.04 max	0.03 max	1.0 max	-
S32750	SAF 2507	0.24 - 0.32	6.0 - 8.0	0.04 max	0.02 max	0.8 max	-
S32760	Zeron 100	0.20 - 0.30	6.0 - 8.0	0.03 max	0.01 max	1.0 max	W 0.5 -1.0
S32950	7-Mo PLUS	0.15 - 0.35	3.5 - 5.2	0.04 max	0.01 max	0.6 max	-

Table A9: Composition of Candidate Ferritic Stainless Steels

Designation		Compositoin					
UNS	Industry	C%	Cr%	Cu%	Fe%	Mn%	Mo%
S43000	430	0.12 max	16.0 - 18.0	-	balance	1.0 max	-
S44627	E-Brite	0.01 max	25.0 - 27.0	0.02 max	balance	0.4 max	0.75 - 1.5
S44635	Monit	0.03 max	24.5 - 26.0	-	balance	1.0 max	3.5 - 4.5
S44660	Sea-Cure	0.03 max	25.0 - 28.0	-	balance	1.0 max	3.0 - 4.0
S44735	29-4C	0.03 max	28.0 - 30.0	-	balance	1.0 max	3.6 - 4.2
S44800	29-4-2	0.01 max	28.0 - 30.0	0.15 max	balance	0.3 max	3.5 - 4.2

Designation		Composition					
UNS	Industry	N%	Ni%	P%	S%	Si%	% Other
S43000	430	-	-	0.04 max	0.03 max	1.0 max	-
S44627	E-Brite	0.02 max	0.50 max	0.02 max	0.02 max	0.40 max	-
S44635	Monit	0.04 max	3.5 - 4.5	0.04 max	0.03 max	0.75 max	-
S44660	Sea-Cure	0.04 max	1.0 - 3.5	0.04 max	0.03 max	1.0 max	-
S44735	29-4C	0.05 max	1.0 max	0.04 max	0.03 max	1.0 max	-
S44800	29-4-2	0.02 max	2.0 - 2.5	0.03 max	0.20 max	0.20 max	-

Table A10: Composition of Candidate Aluminum Alloy

Designation		Composition				
UNS	Industry	Al%	Cr%	Cu%	Fe%	Mg%
A92014	2014 O	balance	0.10 max	3.9 - 5.0	0.7 max	-
A93003	Alcad 3003 H14	balance	-	0.05 - 0.20	0.7 max	-
A93004	3004 H32	balance	-	0.25 max	0.7 max	0.8 - 1.3
A94043	4043 H16	balance	-	0.3 max	0.8 max	0.05 max
A95052	5052 H34	balance	0.15 - 0.35	0.10 max	0.40 max	2.2 - 2.8
A95083	5083 O	balance	0.05 - 0.25	0.10 max	0.40 max	4.0 - 4.9
A95086	5086 H34	balance	0.05 - 0.25	0.10 max	0.50 max	3.5 - 4.5
A96061	6061 T6	balance	0.04 - 0.35	0.15 - 0.40	0.7 max	0.8 - 1.2
A96063	6063 T4	balance	0.10 max	0.10 max	0.35 max	0.45 - 0.9
A97072	7072	balance	-	0.10 max	-	0.10 max
A97075	7075 O	balance	0.18 - 0.28	1.2 - 2.0	0.50 max	2.1 - 2.9

Designation		Composition				
UNS	Industry	Mn%	Si%	Ti%	Zn%	% Other
A92014	2014 O	0.4 - 1.2	0.5 - 1.2	0.15 max	0.25 max	-
A93003	Alcad 3003 H14	1.0 - 1.5	0.6 max	-	0.10 max	-
A93004	3004 H32	1.0 - 1.5	0.30 max	-	0.25 max	-
A94043	4043 H16	0.05 max	4.5 - 6.0	0.20 max	0.10 max	-
A95052	5052 H34	0.10 max	0.25 max	-	0.10 max	-
A95083	5083 O	0.4 - 1.0	0.40 max	0.15 max	0.25 max	-
A95086	5086 H34	0.2 - 0.7	0.40 max	0.15 max	0.25 max	-
A96061	6061 T6	0.15 max	0.4 - 0.8	0.15 max	0.25 max	-
A96063	6063 T4	0.10 max	0.20 - 0.6	0.10 max	0.10 max	-
A97072	7072	0.10 max	-	-	0.8 - 1.3	-
A97075	7075 O	0.30 max	0.40 max	0.20 max	5.1 - 6.1	-

Table A11: Composition of Candidate Nickel Alloys

Designation		Composition							
UNS	Industry	Al%	C%	Co%	Cr%	Cu%	Fe%	Mn%	Mo%
N04400	Monel 400	-	0.30 max	-	-	28.0 - 34.0	2.5 max	2.0 max	-
N04405	Monel 405	-	0.30 max	-	-	28.0 - 34.0	2.5 max	2.0 max	-
N05500	Monel K-500	2.3 - 3.2	0.18 max	-	-	27.0 - 33.0	2.0 max	1.5 max	-
N06022	C-22	-	0.02 max	2.5 max	20.0 - 23.0	-	2.0 - 6.0	0.50 max	12.5 - 14.5
N06030	G-30	-	0.03 max	5.0 max	28.0 - 31.5	-	13.0 - 17.0	1.5 max	4.0 - 6.0
N06059	Alloy 59	0.1 - 0.4	-	-	22.0 - 24.0	-	1.5 max	0.50 max	16.5 max
N06200	C-2000	-	0.01 max	2.0 max	22.0 - 24.0	1.3 - 1.9	3.0 max	0.50 max	15.0 - 17.0
N06625	Alloy 625	0.4	0.10 max	1.0 max	20.0 - 23.0	-	5.0 max	0.50 max	8.0 - 10.0
N07718	Alloy 718	0.2 - 0.8	0.08 max	1.0 max	17.0 - 21.0	0.30 max	balance	0.35 max	2.8 - 3.3
N09925	Alloy 925	0.1 - 0.5	0.03 max	-	19.5 - 22.5	1.5 - 3.0	22.0 min	1.0 max	2.5 - 3.5
N06686	Alloy 686	-	0.01 max	-	19.0 - 23.0	-	1.0 max	0.75 max	15.0 - 17.0
N08926	1925hMo	-	0.02 max	-	20.0 - 21.0	0.8 - 1.0	0.40 max	1.0 max	6.0 - 6.8
N10276	C-276	-	0.01 max	2.5 max	14.5 - 16.5	-	4.0 - 7.0	1.0 max	15.0 - 17.0
R20033	Alloy 33	-	0.02 max	-	31.0 - 35.0	0.3 - 1.2	balance	2.0 max	0.50 - 2.0

Designation		Composition						
UNS	Industry	Ni%	P%	S%	Si%	Ti	W%	% Other
N04400	Monel 400	balance	-	0.03 max	0.50 max	-	-	-
N04405	Monel 405	balance	-	0.02 - 0.06	0.50 max	-	-	-
N05500	Monel K-500	balance	-	0.10 max	0.50 max	0.35 - 0.85	-	
N06022	C-22	balance	0.02 max	0.02 max	0.08 max	-	2.5 - 3.5	V 0.35 max
N06030	G-30	balance	0.04 max	0.02 max	0.8 max	-	1.5 - 4.0	Cb+Ta 0.3-1.5
N06059	Alloy 59	balance	0.02 max	-	0.10 max	-	-	-
N06200	C-2000	balance	0.03 max	0.01 max	0.08 max	-	-	-
N06625	Alloy 625	balance	0.02 max	0.02 max	0.50 max	0.40 max	-	Nb+Ta 4.15
N07718	Alloy 718	50.0 - 55.0	0.02 max	0.02 max	0.35 max	0.65 - 1.15	-	Nb 4.7 - 5.7
N09925	Alloy 925	balance	-	0.03 max	0.5 max	1.9 - 2.4	-	Nb 0.5 max
N06686	Alloy 686	balance	0.04 max	0.02 max	0.08 max	0.02 - 0.25	3.0 - 4.4	-
N08926	1925hMo	balance	0.03 max	0.01 max	0.50 max	-	-	N 0.18 - 0.20
N10276	C-276	balance	0.04 max	0.03 max	0.08 max	-	3.0 - 4.5	-
R20033	Alloy 33	30.0 - 33.0	0.02 max	0.01 max	0.50 max	-	-	N 0.35 - 0.60

Table A12: Composition of Candidate Copper Alloys

Designation		Composition					
UNS	Industry	Al%	C%	Cr%	Cu%	Fe%	Mn%
C61400	Al Bronze	6.0 - 8.0	-	-	balance	1.5 - 3.5	1.0 max
C63000	NiAl Bronze	9.0 - 11.0	-	-	balance	2.0 - 4.0	1.5 max
C70600	90-10 CuproNi	-	-	-	balance	1.0 - 1.8	1.0 max
C71500	70-30 CuproNi	-	-	-	balance	0.40 - 1.0	1.0 max
C72200	CuproNi w/ Cr	-	0.03 max	0.30 - 0.7	balance	0.5 - 1.0	1.0 max
C83600	85-5-5-5	0.01 max	-	-	balance	0.30 max	-
C86500	Mn Bronze	0.5 - 1.5	-	-	balance	0.40 - 2.0	0.10 - 1.5
C95500	Al Bronze 9D	10.0 - 11.5	-	-	balance	3.0 - 5.0	3.5 max
C95700	MnAl Bronze	7.0 - 8.5	-	-	balance	2.0 - 4.0	11.0 - 14.0
C95800	Alpha NiAl Brnz	8.5 - 9.5	-	-	balance	3.5 - 4.5	0.8 - 1.5
C96200	90 Cu-10 Ni	-	0.10 max	-	balance	1.0 - 1.8	1.5 max
C96400	70-30 CuNi	-	0.20 max	-	balance	0.25 - 1.5	1.5 max

Designation		Composition					
UNS	Industry	Ni%	Pb%	Si%	Sn%	Zn%	% Other
C61400	Al Bronze	-	0.01 max	-	-	0.20 max	-
C63000	NiAl Bronze	4.0 - 5.5	-	0.25 max	0.2 max	-	
C70600	90-10 CuproNi	9.0 - 11.0	0.05 max	-	-	1.0 max	-
C71500	70-30 CuproNi	29.0 - 33.0	0.05 max	-	-	1.0 max	-
C72200	CuproNi w/ Cr	15.0 - 18.0	0.05 max	0.03 max	-	1.0 max	Ti 0.03 max
C83600	85-5-5-5	1.0 max	4.0 - 6.0	0.01 max	4.0 - 6.0	4.0 - 6.0	-
C86500	Mn Bronze	1.0 max	0.40 max	-	1.0 max	36.0 - 42.0	-
C95500	Al Bronze 9D	3.0 - 5.5	-	-	-	-	-
C95700	MnAl Bronze	1.5 - 3.0	-	0.10 max	-	-	-
C95800	Alpha NiAl Brnz	4.0 - 5.0	0.03 max	0.10 max	-	-	-
C96200	90 Cu-10 Ni	9.0 - 11.0	0.01 max	0.50 max	-	-	Nb 0.40, S 0.02
C96400	70-30 CuNi	28.0 - 32.0	0.03 max	0.50 max	-	-	-

Appendix B

Fuzzy Logic Simplifying Rules and Evaluation Results

Table B1: Simplifying Rules for Pressure Vessel Material Selection with Price

		Price		Corrosion		Strength		Weldability		Toughness		Output
1	IF	B	AND	B	AND	N	AND	N	AND	N	THEN	T
2	IF	B	AND	G	AND	N	AND	E	AND	E	THEN	A
3	IF	B	AND	G	AND	N	AND	(E)	AND	N	THEN	B
4	IF	B	AND	G	AND	N	AND	B	AND	(E)	THEN	B
5	IF	B	AND	E	AND	(B)	AND	(B)	AND	E	THEN	G
6	IF	B	AND	E	AND	(B)	AND	E	AND	(B)	THEN	G
7	IF	B	AND	E	AND	N	AND	G	AND	G	THEN	A
8	IF	B	AND	E	AND	B	AND	N	AND	N	THEN	B
9	IF	B	AND	E	AND	N	AND	B	AND	N	THEN	B
10	IF	B	AND	E	AND	N	AND	N	AND	B	THEN	B
11	IF	G	AND	B	AND	N	AND	E	AND	E	THEN	B
12	IF	G	AND	B	AND	N	AND	(E)	AND	N	THEN	T
13	IF	G	AND	B	AND	N	AND	N	AND	(E)	THEN	T
14	IF	G	AND	G	AND	(B)	AND	E	AND	E	THEN	E
15	IF	G	AND	G	AND	(B)	AND	G	AND	G	THEN	G
16	IF	G	AND	G	AND	N	AND	E	AND	G	THEN	G
17	IF	G	AND	G	AND	N	AND	G	AND	E	THEN	G
18	IF	G	AND	G	AND	N	AND	B	AND	B	THEN	B
19	IF	G	AND	G	AND	(B)	AND	(B)	AND	B	THEN	A
20	IF	G	AND	G	AND	(B)	AND	B	AND	(B)	THEN	A
21	IF	G	AND	G	AND	B	AND	(B)	AND	(B)	THEN	A
22	IF	G	AND	G	AND	B	AND	B	AND	N	THEN	B
23	IF	G	AND	G	AND	B	AND	N	AND	B	THEN	B
24	IF	G	AND	E	AND	N	AND	(B)	AND	(B)	THEN	E
25	IF	G	AND	E	AND	(E)	AND	B	AND	B	THEN	A
26	IF	G	AND	E	AND	E	AND	B	AND	B	THEN	G
27	IF	G	AND	E	AND	N	AND	B	AND	(B)	THEN	G
28	IF	G	AND	E	AND	N	AND	(B)	AND	B	THEN	G
29	IF	E	AND	B	AND	(B)	AND	E	AND	E	THEN	G
30	IF	E	AND	B	AND	B	AND	E	AND	E	THEN	A
31	IF	E	AND	B	AND	N	AND	B	AND	N	THEN	B
32	IF	E	AND	B	AND	N	AND	N	AND	B	THEN	B
33	IF	E	AND	B	AND	N	AND	G	AND	G	THEN	A
34	IF	E	AND	B	AND	N	AND	E	AND	G	THEN	A
35	IF	E	AND	B	AND	N	AND	E	AND	G	THEN	A
36	IF	E	AND	G	AND	N	AND	(B)	AND	E	THEN	E
37	IF	E	AND	G	AND	N	AND	E	AND	(B)	THEN	E
38	IF	E	AND	G	AND	(E)	AND	G	AND	G	THEN	G
39	IF	E	AND	G	AND	E	AND	G	AND	G	THEN	E
40	IF	E	AND	G	AND	N	AND	B	AND	(B)	THEN	A
41	IF	E	AND	G	AND	B	AND	(B)	AND	B	THEN	A
42	IF	E	AND	G	AND	(B)	AND	(B)	AND	B	THEN	G
43	IF	E	AND	G	AND	N	AND	B	AND	B	THEN	B
44	IF	E	AND	E	AND	N	AND	N	AND	N	THEN	E

T: terrible, B: bad, A: average G: good, E: excellent, N: none, ( ) : all conditions except

Table B2: Simplifying Rules for Pressure Vessel Material Selection without Price

		Corrosion		Strength		Weldability		Toughness		Performance
1	IF	B	AND	N	AND	(E)	AND	N	THEN	T
2	IF	B	AND	E	AND	E	AND	E	THEN	A
3	IF	B	AND	(E)	AND	E	AND	N	THEN	B
4	IF	B	AND	N	AND	E	AND	(E)	THEN	B
5	IF	G	AND	(B)	AND	E	AND	(B)	THEN	G
6	IF	G	AND	B	AND	E	AND	N	THEN	B
7	IF	G	AND	(B)	AND	E	AND	B	THEN	A
8	IF	G	AND	E	AND	G	AND	E	THEN	G
9	IF	G	AND	G	AND	G	AND	E	THEN	G
10	IF	G	AND	E	AND	G	AND	G	THEN	G
11	IF	G	AND	G	AND	G	AND	G	THEN	A
12	IF	G	AND	B	AND	G	AND	(B)	THEN	B
13	IF	G	AND	(B)	AND	G	AND	B	THEN	B
14	IF	G	AND	B	AND	G	AND	B	THEN	T
15	IF	G	AND	E	AND	B	AND	(B)	THEN	A
16	IF	G	AND	G	AND	B	AND	E	THEN	A
17	IF	G	AND	G	AND	B	AND	G	THEN	B
18	IF	G	AND	(B)	AND	B	AND	B	THEN	B
19	IF	G	AND	B	AND	B	AND	(B)	THEN	B
20	IF	G	AND	B	AND	B	AND	B	THEN	T
21	IF	E	AND	(B)	AND	E	AND	(B)	THEN	E
22	IF	E	AND	B	AND	E	AND	(B)	THEN	A
23	IF	E	AND	(B)	AND	E	AND	B	THEN	G
24	IF	E	AND	B	AND	E	AND	B	THEN	B
25	IF	E	AND	E	AND	G	AND	E	THEN	E
26	IF	E	AND	G	AND	G	AND	E	THEN	G
27	IF	E	AND	E	AND	G	AND	G	THEN	G
28	IF	E	AND	G	AND	G	AND	G	THEN	G
29	IF	E	AND	G	AND	G	AND	B	THEN	A
30	IF	E	AND	B	AND	G	AND	G	THEN	A
31	IF	E	AND	B	AND	G	AND	B	THEN	B

T: terrible, B: bad, A: average G: good, E: excellent, N: none, ( ) : all conditions except

Table B3: Simplifying Rules for Turbine Blade Material Selection

		Density		Weldability		Corrosion		Toughness		Strength		Performance
1	IF	B	AND	N	AND	N	AND	N	AND	N	THEN	T
2	IF	G	AND	E	AND	(B)	AND	(B)	AND	(B)	THEN	G
3	IF	G	AND	E	AND	(B)	AND	B	AND	(B)	THEN	A
4	IF	G	AND	E	AND	(B)	AND	(B)	AND	B	THEN	A
5	IF	G	AND	E	AND	B	AND	(B)	AND	(B)	THEN	A
6	IF	G	AND	E	AND	B	AND	(B)	AND	B	THEN	B
7	IF	G	AND	E	AND	(B)	AND	B	AND	B	THEN	B
8	IF	G	AND	E	AND	B	AND	B	AND	(B)	THEN	B
9	IF	G	AND	E	AND	B	AND	B	AND	B	THEN	T
10	IF	G	AND	G	AND	(B)	AND	(B)	AND	(B)	THEN	A
11	IF	G	AND	G	AND	(B)	AND	B	AND	(B)	THEN	B
12	IF	G	AND	G	AND	(B)	AND	(B)	AND	B	THEN	B
13	IF	G	AND	G	AND	B	AND	(B)	AND	(B)	THEN	B
14	IF	G	AND	G	AND	B	AND	(B)	AND	B	THEN	T
15	IF	G	AND	G	AND	(B)	AND	B	AND	B	THEN	T
16	IF	G	AND	G	AND	B	AND	B	AND	(B)	THEN	T
17	IF	G	AND	G	AND	B	AND	B	AND	B	THEN	T
18	IF	G	AND	B	AND	(B)	AND	(B)	AND	(B)	THEN	B
19	IF	G	AND	B	AND	N	AND	B	AND	N	THEN	T
20	IF	G	AND	B	AND	N	AND	N	AND	B	THEN	T
21	IF	G	AND	B	AND	B	AND	N	AND	N	THEN	T
22	IF	E	AND	E	AND	(B)	AND	(B)	AND	(B)	THEN	E
23	IF	E	AND	E	AND	(B)	AND	B	AND	(B)	THEN	G
24	IF	E	AND	E	AND	B	AND	(B)	AND	(B)	THEN	G
25	IF	E	AND	E	AND	(B)	AND	(B)	AND	B	THEN	G
26	IF	E	AND	E	AND	B	AND	(B)	AND	B	THEN	A
27	IF	E	AND	E	AND	(B)	AND	B	AND	B	THEN	A
28	IF	E	AND	E	AND	B	AND	B	AND	(B)	THEN	A
29	IF	E	AND	E	AND	B	AND	B	AND	B	THEN	B
30	IF	E	AND	G	AND	(B)	AND	(B)	AND	(B)	THEN	G
31	IF	E	AND	G	AND	(B)	AND	B	AND	(B)	THEN	A
32	IF	E	AND	G	AND	(B)	AND	(B)	AND	B	THEN	A
33	IF	E	AND	G	AND	B	AND	(B)	AND	(B)	THEN	A
34	IF	E	AND	G	AND	B	AND	(B)	AND	B	THEN	B
35	IF	E	AND	G	AND	(B)	AND	B	AND	B	THEN	B
36	IF	E	AND	G	AND	B	AND	B	AND	(B)	THEN	B
37	IF	E	AND	G	AND	B	AND	B	AND	B	THEN	T
38	IF	E	AND	B	AND	(B)	AND	(B)	AND	(B)	THEN	A
39	IF	E	AND	B	AND	(B)	AND	B	AND	(B)	THEN	B
40	IF	E	AND	B	AND	(B)	AND	(B)	AND	B	THEN	B
41	IF	E	AND	B	AND	B	AND	(B)	AND	(B)	THEN	B
42	IF	E	AND	B	AND	B	AND	(B)	AND	B	THEN	T
43	IF	E	AND	B	AND	(B)	AND	B	AND	B	THEN	T
44	IF	E	AND	B	AND	B	AND	B	AND	(B)	THEN	T
45	IF	E	AND	B	AND	B	AND	B	AND	B	THEN	T

T: terrible, B: bad, A: average G: good, E: excellent, N: none, ( ) : all conditions except

Table B4: Simplifying Rules for Drive Shaft Material Selection

		Hardness		Strength		Machinability		Toughness		Output
1	IF	E	AND	E	AND	E	AND	N	THEN	E
2	IF	E	AND	E	AND	E	AND	B	THEN	G
3	IF	E	AND	E	AND	G	AND	E	THEN	E
4	IF	E	AND	E	AND	G	AND	(E)	THEN	G
5	IF	E	AND	E	AND	B	AND	(B)	THEN	A
6	IF	E	AND	E	AND	B	AND	B	THEN	B
7	IF	E	AND	G	AND	E	AND	E	THEN	E
8	IF	E	AND	G	AND	E	AND	(E)	THEN	G
9	IF	E	AND	G	AND	G	AND	(B)	THEN	G
10	IF	E	AND	G	AND	G	AND	B	THEN	A
11	IF	E	AND	G	AND	B	AND	(B)	THEN	A
12	IF	E	AND	G	AND	B	AND	B	THEN	B
13	IF	G	AND	E	AND	E	AND	(B)	THEN	E
14	IF	G	AND	E	AND	E	AND	B	THEN	A
15	IF	G	AND	E	AND	G	AND	(B)	THEN	G
16	IF	G	AND	E	AND	G	AND	B	THEN	A
17	IF	G	AND	E	AND	B	AND	(B)	THEN	A
18	IF	G	AND	E	AND	B	AND	B	THEN	B
19	IF	G	AND	G	AND	E	AND	(B)	THEN	G
20	IF	G	AND	G	AND	E	AND	B	THEN	A
21	IF	G	AND	G	AND	G	AND	(B)	THEN	A
22	IF	G	AND	G	AND	G	AND	B	THEN	B
23	IF	G	AND	G	AND	B	AND	(B)	THEN	B
24	IF	G	AND	G	AND	B	AND	B	THEN	T
25	IF	B	AND	N	AND	N	AND	N	THEN	T
26	IF	N	AND	B	AND	N	AND	N	THEN	T

T: terrible, B: bad, A: average G: good, E: excellent, N: none, ( ) : all conditions except

Table B5: Simplifying Rules for Mooring Connection

		Strng		Corrosion		Toughness		Hardness		Weldability		Output
1	IF	B	AND	N	AND	N	AND	N	AND	N	THEN	T
2	IF	(B)	AND	E	AND	E	AND	(B)	AND	(B)	THEN	E
3	IF	(B)	AND	E	AND	E	AND	(B)	AND	B	THEN	G
4	IF	(B)	AND	E	AND	E	AND	B	AND	(B)	THEN	G
5	IF	(B)	AND	E	AND	E	AND	B	AND	B	THEN	A
6	IF	(B)	AND	E	AND	G	AND	E	AND	E	THEN	E
7	IF	(B)	AND	E	AND	G	AND	E	AND	G	THEN	E
8	IF	(B)	AND	E	AND	G	AND	G	AND	E	THEN	E
9	IF	(B)	AND	E	AND	G	AND	G	AND	G	THEN	G
10	IF	(B)	AND	E	AND	G	AND	(B)	AND	B	THEN	A
11	IF	(B)	AND	E	AND	G	AND	B	AND	(B)	THEN	A
12	IF	(B)	AND	E	AND	G	AND	B	AND	B	THEN	T
13	IF	(B)	AND	E	AND	B	AND	(B)	AND	(B)	THEN	A
14	IF	(B)	AND	E	AND	B	AND	(B)	AND	B	THEN	B
15	IF	(B)	AND	E	AND	B	AND	B	AND	(B)	THEN	B
16	IF	(B)	AND	E	AND	B	AND	B	AND	B	THEN	T
17	IF	(B)	AND	G	AND	E	AND	E	AND	E	THEN	E
18	IF	(B)	AND	G	AND	E	AND	G	AND	E	THEN	E
19	IF	(B)	AND	G	AND	E	AND	E	AND	G	THEN	E
20	IF	(B)	AND	G	AND	E	AND	G	AND	G	THEN	G
21	IF	(B)	AND	G	AND	E	AND	(B)	AND	B	THEN	A
22	IF	(B)	AND	G	AND	E	AND	B	AND	(B)	THEN	A
23	IF	(B)	AND	G	AND	E	AND	B	AND	B	THEN	B
24	IF	(B)	AND	G	AND	G	AND	E	AND	E	THEN	G
25	IF	(B)	AND	G	AND	G	AND	G	AND	E	THEN	G
26	IF	(B)	AND	G	AND	G	AND	E	AND	G	THEN	G
27	IF	(B)	AND	G	AND	G	AND	G	AND	G	THEN	A
28	IF	(B)	AND	G	AND	G	AND	(B)	AND	B	THEN	A
29	IF	(B)	AND	G	AND	G	AND	B	AND	(B)	THEN	A
30	IF	(B)	AND	G	AND	G	AND	B	AND	B	THEN	B
31	IF	(B)	AND	G	AND	B	AND	(B)	AND	E	THEN	A
32	IF	(B)	AND	G	AND	B	AND	E	AND	(B)	THEN	A
33	IF	(B)	AND	G	AND	B	AND	G	AND	G	THEN	B
34	IF	(B)	AND	G	AND	B	AND	N	AND	B	THEN	T
35	IF	(B)	AND	G	AND	B	AND	B	AND	N	THEN	T
36	IF	(B)	AND	B	AND	E	AND	(B)	AND	E	THEN	A
37	IF	(B)	AND	B	AND	E	AND	E	AND	(B)	THEN	A
38	IF	(B)	AND	B	AND	E	AND	B	AND	N	THEN	T
39	IF	(B)	AND	B	AND	E	AND	B	AND	N	THEN	T
40	IF	(B)	AND	B	AND	G	AND	E	AND	E	THEN	B
41	IF	(B)	AND	B	AND	G	AND	(E)	AND	N	THEN	T
42	IF	(B)	AND	B	AND	G	AND	N	AND	(E)	THEN	T
43	IF	(B)	AND	B	AND	B	AND	N	AND	N	THEN	T

T: terrible, B: bad, A: average G: good, E: excellent, N: none, ( ) : all conditions except

Table B6: Fuzzy Logic Material Selection Performance Indices

Candidate Alloys	Fuzzy Logic Performance Indices				
Industry	PV w/ cost	PV w/o cost	Turbine Blades	Drive Shaft	Mooring Connection
304	42.95	16.66	30.63	39.74	2.15
316	50.51	35.39	38.32	46.44	36.78
316L	50.51	35.39	38.02	39.73	40.08
317L	65.13	53.38	48.10	31.94	56.35
317LM	71.36	54.29	47.28	31.94	54.64
254 SMO	59.07	45.18	46.09	29.36	45.14
AL-6XN	79.45	80.33	50.35	47.45	79.80
Alloy 825	52.99	54.84	46.55	10.78	44.65
904L	75.67	75.33	53.67	1.44	55.85
1925hMo	67.12	55.33	47.43	10.78	52.24
2205	78.51	54.44	37.44	41.40	57.70
2304	35.16	17.14	23.81	40.40	30.36
Ferralium 255	84.97	67.99	37.62	53.54	58.86
SAF 2507	86.86	68.52	37.79	59.10	73.09
Zeron 100	86.86	68.50	37.09	53.66	56.70
7-Mo PLUS	73.46	50.41	38.55	42.30	52.95
430	35.35	1.44	16.66	22.59	2.15
E-Brite	21.29	20.30	11.55	16.93	5.98
Monit	26.64	22.39	11.21	29.56	4.93
Sea-Cure	22.03	22.39	10.76	25.38	3.06
29-4C	26.48	22.28	10.64	22.48	4.93
29-4-2	24.17	22.28	10.76	22.48	3.68
Monel 400	60.41	51.43	15.85	1.44	44.72
Monel R-405	60.41	47.18	15.85	1.44	44.00
Monel K-500	46.52	42.16	36.62	50.00	47.06
C-22	46.60	81.41	30.35	48.19	83.21
G-30	61.61	80.56	44.94	1.44	59.58
Alloy 59	67.32	83.34	33.53	63.77	96.20
C-2000	41.04	57.23	29.57	10.28	25.29
Alloy 625	51.90	59.39	37.44	45.79	58.46
Alloy 718	54.42	44.56	41.79	50.00	56.05
Alloy 925	53.24	54.92	46.93	50.00	54.85
Alloy 686	79.38	97.22	28.89	49.28	90.89
C-276	78.04	98.56	19.74	31.94	89.48
Alloy 33	81.00	78.00	55.62	50.00	87.97
2014 O			24.43		
Alcad 3003 H14			25.75		
3004 H32			35.00		
4043 H16			36.88		
5052 H34			42.66		
5083 O			31.03		
5086 H34			47.63		
6061 T6			49.20		
6063 T4			23.99		
7072			24.37		
7075 O			25.39		

Table B7: Fuzzy Logic Material Selection Performance Indices Normalized to Cost

Candidate Alloys	Fuzzy Logic Performance Indices Normalized to Price			
Industry	PV w/o cost	Turbine Blades	Drive Shaft	Mooring Connection
304	17.00	31.26	40.55	2.20
316	27.44	29.71	36.00	28.51
316L	27.44	29.47	30.80	31.07
317L	36.56	32.94	21.87	38.59
317LM	32.90	28.65	19.36	33.12
254 SMO	23.05	23.52	14.98	23.03
AL-6XN	34.18	21.43	20.19	33.96
Alloy 825	21.17	17.97	4.16	17.24
904L	33.78	24.07	0.65	25.04
1925hMo	23.85	20.45	4.65	22.52
2205	49.49	34.04	37.64	52.46
2304	19.25	26.76	45.39	34.11
Ferralium 255	55.73	30.83	43.88	48.25
SAF 2507	52.70	29.07	45.46	56.22
Zeron 100	53.94	29.20	42.25	44.64
7-Mo PLUS	47.56	36.37	39.91	49.96
430	1.78	20.57	27.89	2.66
E-Brite	21.37	12.16	17.82	6.29
Monit	19.47	9.75	25.71	4.28
Sea-Cure	21.12	10.15	23.94	2.88
29-4C	21.02	10.04	21.21	4.65
29-4-2	20.25	9.78	20.44	3.34
Monel 400	13.05	4.02	0.37	11.35
Monel R-405	11.98	4.02	0.37	11.17
Monel K-500	10.39	9.02	12.32	11.59
C-22	15.96	5.95	9.45	16.32
G-30	19.18	10.70	0.34	14.19
Alloy 59	17.77	7.15	13.60	20.51
C-2000	12.10	6.25	2.17	5.35
Alloy 625	12.85	8.10	9.91	12.65
Alloy 718	13.14	12.33	14.75	16.53
Alloy 925	16.49	14.09	15.02	16.47
Alloy 686	19.72	5.86	10.00	18.44
C-276	17.85	3.58	5.79	16.21
Alloy 33	31.84	22.70	20.41	35.91
2014 O		29.44		
Alcad 3003 H14		34.80		
3004 H32		44.88		
4043 H16		45.53		
5052 H34		52.67		
5083 O		34.47		
5086 H34		54.12		
6061 T6		64.74		
6063 T4		32.42		
7072		32.50		
7075 O		23.73		

Appendix C

Weighted Properties Method Material Selections

Table C1: Calculation of Weighting Factors for Pressure Vessel Including Price

Material Properties	Price	PREN	Yield Strength	Weldability	Impact Strength	Positive Decisions	Weighting Factor
Price	1	2	3	2	2	10	0.38
PREN	0	1	2	2	2	7	0.27
Yield Strength	0	0	1	0	1	2	0.08
Weldability	0	0	2	1	1	4	0.15
Impact Strength	0	0	1	1	1	3	0.12
Total Number of Positive Decisions						26	

Table C2: Calculation of Weighting Factors for Pressure Vessel Not Including Price

Material Properties	Corrosion	Yield Strength	Weldability	Impact Strength	Positive Decisions	Weighting Factor
Corrosion	1	3	2	2	8	0.47
Yield Strength	0	1	0	1	2	0.12
Weldability	0	2	1	1	4	0.24
Impact Strength	0	1	1	1	3	0.17
Total Number of Positive Decisions					17	

Table C3: Calculation of Weighting Factors for Turbine Blades

Material Properties	Density	Strength	Corrosion	Weldability	Impact Strength	Positive Decisions	Weighting Factor
Density	1	3	2	1	2	9	0.36
Strength	0	1	0	0	0	1	0.04
Corrosion	0	2	1	0	1	4	0.16
Weldability	1	2	2	1	1	7	0.28
Impact Strength	0	2	1	0	1	4	0.16
Total Number of Positive Decisions						25	

Table C4: Calculation of Weighting Factors for Drive Shaft

Material Properties	Hardness	Strength	Machinability	Impact Strength	Positive Decisions	Weighting Factor
Hardness	1	1	2	2	6	0.35
Strength	1	1	2	2	6	0.35
Machinability	0	1	1	1	3	0.18
Impact Strength	0	0	1	1	2	0.12
Total Number of Positive Decisions					17	

Table C5: Calculation of Weighting Factors for Mooring Connection Points

Material Properties	Hardness	PREN	Yield Strength	Weldability	Impact Strength	Positive Decisions	Weighting Factor
Hardness	1	0	0	1	0	2	0.08
PREN	2	1	1	2	2	8	0.32
Yield Strength	2	1	1	2	2	8	0.32
Weldability	1	0	0	1	0	2	0.08
Impact Strength	2	0	0	2	1	5	0.20
Total Number of Positive Decisions						25	

Table C6: Weighted Performance Indices for Pressure Vessel Including Cost

Candidate Alloy	Scaled Cost * 0.39	Scaled PREN * 0.27	Scaled Yield Strength * 0.08	Scaled Weldability * 0.15	Scaled Impact Strength * 0.12	Performance Index
304	31.4	6.8	1.6	12.0	6.0	57.8
316	23.9	8.9	1.6	12.0	5.9	52.2
316L	23.9	8.9	1.4	12.0	5.9	52.0
317L	21.1	10.7	1.9	12.0	5.9	51.5
317LM	18.7	12.1	1.6	12.0	5.9	50.2
254 SMO	15.7	15.3	2.4	12.0	3.3	48.7
AL-6XN	13.1	17.1	2.9	15.0	5.7	53.8
Alloy 825	11.9	11.4	2.4	15.0	3.3	44.0
904L	13.8	12.8	2.2	15.0	5.7	49.5
1925hMo	13.3	14.9	2.4	12.0	4.5	47.1
2205	28.0	12.8	3.6	9.0	7.5	60.9
2304	34.6	8.5	3.2	9.0	3.5	58.8
Ferralium 255	25.2	13.9	4.4	9.0	5.7	58.2
SAF 2507	23.7	14.6	4.4	9.0	6.6	58.2
Zeron 100	24.2	14.2	4.4	9.0	6.8	58.6
7-Mo PLUS	29.0	13.1	3.8	9.0	4.7	59.7
430	38.0	6.0	1.6	6.0	6.5	58.2
E-Brite	32.4	10.7	2.2	3.0	2.3	50.5
Monit	26.8	15.3	4.1	3.0	2.1	51.3
Sea-Cure	29.0	13.9	3.6	3.0	2.1	51.6
29-4C	29.0	15.3	3.3	3.0	2.1	52.7
29-4-2	28.0	14.9	3.3	3.0	2.1	51.3
Monel 400	7.8	10.7	1.9	9.0	8.1	37.5
Monel R-405	7.8	10.7	1.9	9.0	7.6	37.0
Monel K-500	7.6	12.4	6.3	12.0	3.0	41.3
C-22	6.0	17.1	3.0	12.0	10.5	48.5
G-30	7.3	16.7	2.5	12.0	10.5	49.0
Alloy 59	6.6	27.0	3.0	12.0	9.0	57.6
C-2000	6.5	27.0	0.9	12.0	10.7	57.1
Alloy 625	6.7	18.5	4.1	12.0	4.0	45.3
Alloy 718	9.1	11.7	8.0	12.0	3.3	44.1
Alloy 925	9.2	12.1	6.5	15.0	3.0	45.8
Alloy 686	6.2	26.3	5.6	12.0	12.0	62.1
C-276	5.6	24.5	2.8	15.0	10.1	58.0
Alloy 33	12.6	13.5	3.0	15.0	9.0	53.1

Table C7: Weighted Performance Indices for Pressure Vessel Not Including Cost

Candidate Alloy	Scaled PREN * 0.47	Scaled Yield Strength * 0.12	Scaled Weldability * 0.23	Scaled Impact Strength * 0.18	Performance Index
304	11.8	2.5	18.4	9.0	41.6
316	15.5	2.5	18.4	8.8	45.1
316L	15.5	2.0	18.4	8.8	44.7
317L	18.6	2.9	18.4	8.8	48.6
317LM	21.0	2.5	18.4	8.8	50.7
254 SMO	26.6	3.6	18.4	5.0	53.5
AL-6XN	29.7	4.4	23.0	8.6	65.6
Alloy 825	19.8	3.6	23.0	5.0	51.3
904L	22.3	3.2	23.0	8.6	57.1
1925hMo	26.0	3.6	18.4	6.8	54.7
2205	22.3	5.4	13.8	11.3	52.7
2304	14.8	4.8	13.8	5.3	38.7
Ferralium 255	24.1	6.6	13.8	8.6	53.1
SAF 2507	25.4	6.6	13.8	9.9	55.7
Zeron 100	24.7	6.6	13.8	10.1	55.3
7-Mo PLUS	22.9	5.8	13.8	7.1	49.5
430	10.5	2.5	9.2	9.8	31.9
E-Brite	18.6	3.3	4.6	3.4	29.8
Monit	26.6	6.2	4.6	3.2	40.5
Sea-Cure	24.1	5.4	4.6	3.2	37.3
29-4C	26.6	5.0	4.6	3.2	39.3
29-4-2	26.0	5.0	4.6	3.2	38.7
Monel 400	18.6	2.9	13.8	12.2	47.4
Monel R-405	18.6	2.9	13.8	11.4	46.6
Monel K-500	21.6	9.5	18.4	4.5	54.0
C-22	29.7	4.4	18.4	15.8	68.3
G-30	29.1	3.7	18.4	15.8	66.9
Alloy 59	47.0	4.6	18.4	13.5	83.5
C-2000	47.0	1.3	18.4	16.1	82.8
Alloy 625	32.2	6.2	18.4	6.0	62.7
Alloy 718	20.4	12.0	18.4	5.0	55.8
Alloy 925	21.0	9.8	23.0	4.5	58.3
Alloy 686	45.8	8.4	18.4	18.0	90.6
C-276	42.7	4.3	23.0	15.2	85.1
Alloy 33	23.5	4.6	23.0	13.5	64.6

Table C8: Weighted Performance Indices for Turbine Blades

Candidate Alloy	Scaled Density * 0.38	Scaled Yield Strength * 0.08	Scaled PREN * 0.08	Scaled Weldability * 0.29	Scaled Impact Strength * 0.17	Performance Index
304	12.6	1.6	2.0	23.2	8.5	48.0
316	12.6	1.6	2.6	23.2	8.3	48.4
316L	12.6	1.4	2.6	23.2	8.3	48.1
317L	12.6	1.9	3.2	23.2	8.3	49.2
317LM	12.6	1.6	3.6	23.2	8.3	49.3
254 SMO	12.6	2.4	4.5	23.2	4.7	47.4
AL-6XN	12.5	2.9	5.1	29.0	8.1	57.6
Alloy 825	12.4	2.4	3.4	29.0	4.7	51.9
904L	12.7	2.2	3.8	29.0	8.1	55.7
1925hMo	12.5	2.4	4.4	23.2	6.4	48.9
2205	12.9	3.6	3.8	17.4	10.6	48.3
2304	13.0	3.2	2.5	17.4	5.0	41.1
Ferralium 255	12.9	4.4	4.1	17.4	8.1	46.9
SAF 2507	13.0	4.4	4.3	17.4	9.4	48.4
Zeron 100	12.9	4.4	4.2	17.4	9.6	48.5
7-Mo PLUS	13.1	3.8	3.9	17.4	6.7	44.9
430	13.0	1.6	1.8	11.6	9.2	37.2
E-Brite	13.2	2.2	3.2	5.8	3.2	27.5
Monit	13.0	4.1	4.5	5.8	3.0	30.4
Sea-Cure	13.1	3.6	4.1	5.8	3.0	29.6
29-4C	13.2	3.3	4.5	5.8	3.0	29.8
29-4-2	13.1	3.3	4.4	5.8	3.0	29.6
Monel 400	11.5	1.9	3.2	17.4	11.5	45.4
Monel R-405	11.5	1.9	3.2	17.4	10.8	44.7
Monel K-500	12.0	6.3	3.7	23.2	4.3	49.4
C-22	11.6	3.0	5.1	23.2	14.9	57.7
G-30	12.3	2.5	4.9	23.2	14.9	57.8
Alloy 59	11.8	3.0	8.0	23.2	12.8	58.7
C-2000	11.9	0.9	8.0	23.2	15.2	59.1
Alloy 625	12.0	4.1	5.5	23.2	5.7	50.4
Alloy 718	12.3	8.0	3.5	23.2	4.7	51.7
Alloy 925	12.4	6.5	3.6	29.0	4.3	55.8
Alloy 686	11.6	5.6	7.8	23.2	17.0	65.2
C-276	11.4	2.8	7.3	29.0	14.3	64.8
Alloy 33	12.8	3.0	4.0	29.0	12.8	61.6
2014 O	36.1	0.8	2.1	29.0	1.1	69.0
Alcad 3003 H14	37.0	0.9	2.1	29.0	0.9	69.9
3004 H32	37.2	1.4	2.1	29.0	1.1	70.7
4043 H16	37.7	1.4	2.1	29.0	0.6	70.9
5052 H34	37.7	1.7	2.1	29.0	1.1	71.6
5083 O	38.0	1.2	2.1	29.0	1.3	71.5
5086 H34	38.0	2.0	2.1	29.0	0.9	72.1
6061 T6	37.4	2.2	2.1	29.0	1.0	71.8
6063 T4	37.6	0.7	2.1	29.0	1.1	70.5
7072	37.2	0.8	2.1	29.0	0.9	69.9
7075 O	36.1	0.8	2.1	29.0	1.3	69.3

Table C9: Weighted Performance Indices for Drive Shaft

Candidate Alloy	Scaled Hardness * 0.35	Scaled Yield Strength * 0.35	Scaled Machinability * 0.18	Scaled Impact Strength * 0.12	Performance Index
304	16.8	7.2	13.5	6.0	43.5
316	18.1	7.2	13.5	5.9	44.6
316L	18.1	6.0	13.5	5.9	43.4
317L	16.0	8.4	13.5	5.9	43.8
317LM	16.0	7.2	13.5	5.9	42.5
254 SMO	18.1	10.5	13.5	3.3	45.4
AL-6XN	18.1	12.8	13.5	5.7	50.1
Alloy 825	14.3	10.5	13.5	3.3	41.6
904L	12.8	9.5	13.5	5.7	41.4
1925hMo	14.3	10.5	13.5	4.5	42.8
2205	23.5	15.8	9.0	7.5	55.8
2304	24.9	14.0	9.0	3.5	51.4
Ferralium 255	24.2	19.3	9.0	5.7	58.2
SAF 2507	27.1	19.3	9.0	6.6	62.0
Zeron 100	23.6	19.3	9.0	6.8	58.6
7-Mo PLUS	24.2	16.8	9.0	4.7	54.7
430	15.2	7.2	13.5	6.5	42.4
E-Brite	16.0	9.6	13.5	2.3	41.4
Monit	16.0	18.0	13.5	2.1	49.6
Sea-Cure	21.1	15.8	13.5	2.1	52.4
29-4C	18.1	14.5	13.5	2.1	48.2
29-4-2	18.1	14.5	13.5	2.1	48.2
Monel 400	11.4	8.4	18.0	8.1	45.9
Monel R-405	10.9	8.4	18.0	7.6	44.9
Monel K-500	26.3	27.7	9.0	3.0	65.9
C-22	18.3	13.0	13.5	10.5	55.2
G-30	12.5	10.9	18.0	10.5	51.9
Alloy 59	28.5	13.3	9.0	9.0	59.8
C-2000	14.3	3.9	13.5	10.7	42.3
Alloy 625	16.6	18.1	13.5	4.0	52.2
Alloy 718	29.0	35.0	9.0	3.3	76.3
Alloy 925	29.4	28.5	9.0	3.0	69.9
Alloy 686	16.0	24.5	13.5	12.0	66.0
C-276	16.0	12.4	13.5	10.1	52.0
Alloy 33	21.0	13.3	13.5	9.0	56.8

Table C10: Weighted Performance Indices for Mooring Connection

Candidate Alloy	Scaled Hardness * 0.08	Scaled PREN * 0.32	Scaled Yield Strength * 0.32	Scaled Weldability * 0.08	Scaled Impact Strength * 0.20	Performance Index
304	3.8	8.0	6.6	6.4	10.0	34.8
316	4.1	10.5	6.6	6.4	9.8	37.4
316L	4.1	10.5	5.4	6.4	9.8	36.3
317L	3.7	12.6	7.7	6.4	9.8	40.1
317LM	3.7	14.3	6.6	6.4	9.8	40.7
254 SMO	4.1	18.1	9.6	6.4	5.5	43.7
AL-6XN	4.1	20.2	11.7	8.0	9.5	53.5
Alloy 825	3.3	13.5	9.6	8.0	5.5	39.8
904L	2.9	15.2	8.6	8.0	9.5	44.2
1925hMo	3.3	17.7	9.6	6.4	7.5	44.4
2205	5.4	15.2	14.4	4.8	12.5	52.2
2304	5.7	10.1	12.8	4.8	5.9	39.3
Ferralium 255	5.5	16.4	17.6	4.8	9.5	53.9
SAF 2507	6.2	17.3	17.6	4.8	11.0	56.9
Zeron 100	5.4	16.8	17.6	4.8	11.3	55.9
7-Mo PLUS	5.5	15.6	15.4	4.8	7.9	49.1
430	3.5	7.2	6.6	3.2	10.9	31.2
E-Brite	3.7	12.6	8.8	1.6	3.8	30.4
Monit	3.7	18.1	16.5	1.6	3.5	43.3
Sea-Cure	4.8	16.4	14.4	1.6	3.5	40.7
29-4C	4.1	18.1	13.3	1.6	3.5	40.6
29-4-2	4.1	17.7	13.3	1.6	3.5	40.2
Monel 400	2.6	12.6	7.7	4.8	13.5	41.2
Monel R-405	2.5	12.6	7.7	4.8	12.7	40.3
Monel K-500	6.0	14.7	25.3	6.4	5.0	57.4
C-22	4.2	20.2	11.8	6.4	17.5	60.1
G-30	2.9	19.8	9.9	6.4	17.5	56.5
Alloy 59	6.5	32.0	12.2	6.4	15.0	72.1
C-2000	3.3	32.0	3.5	6.4	17.9	63.0
Alloy 625	3.8	21.9	16.5	6.4	6.7	55.3
Alloy 718	6.6	13.9	32.0	6.4	5.5	64.4
Alloy 925	6.7	14.3	26.1	8.0	5.0	60.1
Alloy 686	3.7	31.2	22.4	6.4	20.0	83.6
C-276	3.7	29.1	11.4	8.0	16.9	68.9
Alloy 33	4.8	16.0	12.2	8.0	15.0	56.0

Appendix D

Literature Review of Performance of Alloys in Ocean Environment

“Corrosion in Slow Flowing Ocean Thermal Energy Conversion Seawater” (Park and Larsen-Basse 1989)

Larsen-Basse and Park studied the corrosion rates of a number of common alloys in parallel exposure in slowly flowing Hawaiian surface seawater and 590-m deep cold seawater. A brief summary is as follows:

- This study grew out of involvement with the ocean thermal energy conversion development and the Hawaii deep water cable program. Both programs were interested in determining corrosion rates of common alloys in cold deep seawater compared to those in warmer surface waters.

- Various steel, copper, aluminum, zinc and lead alloys were immersed in both warm surface seawater and cold deep seawater for exposure periods of 1, 3, 6, and 10 months and the corrosion effects were compared.

- For the Copper and Cu-30Ni alloys corrosion occurred more rapidly in the colder deep-sea water but leveled off quickly, so that after one year little difference existed between the two waters. Copper corroded approximately 60% faster than Cu-Ni and showed some shallow pitting.

- Stainless steel 304 corroded about 5 times faster in the warm water than in the cold. However the results for 316 showed substantial scatter and no clear trend was indicated.

- Aluminum 6016-T6 showed intense pitting and rapid attack in the cold water, due to its low pH, and minor pitting in the warm water.

“Cathodic Protection of Aluminum in Seawater” (Gundersen and Nisancioglu 1990)

Gundersen and Nisancioglu performed potentiostatic tests on three different aluminum alloys in order to determine the cathodic behavior in natural seawater.

- Tests were performed by immersing specimens of similar size in a 60-L polyvinyl chloride container in which seawater was replaced continuously, maintaining a temperature of 9° C.

- To ascertain information about the transient phenomena between states potentiostatic tests were performed at selected potentials between the pitting potential (-0.75 V_{SCE}) and the cathodic breakdown potential (-1.4 V_{SCE}). Inside this range cathodic protection of aluminum is possible.

- At flow rates of both 2.5 and 8 cm/s specimens were polarized potentiostatically at -0.8, -0.9, -1.0, -1.1, -1.2, and -1.3 V_{SCE}. Control specimens exposed under open circuit conditions were also included in all runs. Cathodic behavior was determined using conventional current-sweep results.

- Low current densities required for the cathodic protection of aluminum alloys result from an etching process, which removes most of the intermetallic particles from the surface without exposing fresh particles from the underlying matrix. Formation of a more continuous insulating oxide leads to an improved passivity and low current densities.

"Aspects of Testing and Selecting Stainless Steel for Seawater Applications" (Steinsmo, Rogne and Drugli)

Steinsmo, Rogne and Drugli reviewed three aspects of testing and selecting stainless steels; electrochemical test methods and their ability to generate data reflecting true corrosion susceptibility, quality control systems, and importance of the repassivation properties.

- Critical crevice indices and critical pitting indices can be used to rank similar materials such as rolled stainless steels. With respect to pitting corrosion, the same index can be used for duplex and austenitic stainless steels. With respect to crevice corrosion different indices must be used.

- Crevice corrosion of highly alloyed stainless steels exposed to natural seawater can propagate at temperatures far lower than the initiation temperature. Repassivation properties of a material are important for material selection and corrosion control.

- Often the stochastic nature of the pitting and crevice corrosion processes in stainless steels are neglected. More specimens need to be tested and at a greater range of temperatures when determining the corrosion resistant properties of stainless steels.

- The differences in heat treatment and product form can be far greater than minor variations in chemical composition. Cast materials, in general, showed less corrosion resistance than forged or rolled materials.

- To determine the rate of crevice corrosion for a given crevice geometry the period of active corrosion should be determined along with the weight loss and depth of corrosion attack.

“Corrosion and Galvanic Compatibility Studies of a High-Strength Copper-Nickel Alloy” (Campbell, Radford, Tuck and Barker 2002)

Campbell, Radford, Tuck and Barker compared the corrosion and galvanic compatibility of a high-strength copper-nickel alloy with that of types 316 and 416 stainless steels in natural seawater.

- The first stages of the copper-nickel alloy corrosion results in film formation containing a high percentage of nickel compounds. Continued exposure leads to the precipitation of Cu_2O with a decreasing nickel content. This resultant surface increases corrosion resistance.

- Continued film dissolution ultimately leads to “islands” of green, non-adherent corrosion products and observable pitting. This results in a par-linear corrosion rate.

- Films formed under static electrolyte conditions are significantly different from those under enhanced flow. Films formed within flowing electrolyte are more protective.

- The copper nickel-nickel and the superduplex stainless steel were protected when coupled to type 316 or type 416 stainless steel with the later exhibiting localized corrosion in response to passive film breakdown.

- The effects of coupling austenitic stainless steels to superduplex stainless steels or copper-nickel alloys has shown to be very unpredictable. A number of factors such as ennoblement of the stainless steel and breakdown of the oxide layers present of the copper-nickel alloy determine the extent of galvanically induced corrosion. Polarity of the couple may vary with time.

“Gasket Selection for Stainless Steels in Seawater” (Francis and Byrne 2007)

Francis and Byrne review published data and recommend combinations to be avoided and the best choice of suitable gaskets.

- For high-alloy stainless steels in seawater use gaskets made of synthetic rubber, rubber bonded aramid, or synthetic fiber for low-pressure systems. Avoid the use of PTFE or graphite-loaded gaskets. For high pressure systems up to 100 bar graphite-containing gaskets are acceptable provided the graphite is sealed from the seawater and is never wetted.

- Only metals compatible with high-alloy stainless steels should be used for spiral-wound gaskets, such as superduplex, 6% Mo austenitic, Ni-Cr-Mo alloys where Mo > 7%, and titanium.

“Comparative Studies of the Seawater Corrosion Behaviour of a Range of Materials” (Al-Malahy and Hodgkiess 2003)

Al-Malahy and Hodgkiess perform a laboratory investigation to compare the corrosion behavior of commercially pure Grade 2 titanium, type 430 ferritic stainless steel, type 316L austenitic stainless steel, type 254SMO superaustenitic stainless steel, and nickel base alloy C-276 in a range of environmental conditions relevant to desalination plant operation.

- The experiments consisted of determining the breakdown potentials of the five metals in varying salinities (35,000 and 55,000 mg/l total dissolved solids), temperature (25° and 45° C), and flow rates (static, mild and severe jet impingement).

- The superior corrosion resistance of titanium was confirmed as was the vulnerability of the lower-alloyed steels.

- Although the superaustenitic stainless steel 254SMO and alloy C-276 exhibited similar resistances to the breakdown of passivity, the nature of the corrosion indicates that the nickel-base alloy is less susceptible to localized corrosion than the superaustenitic stainless steel.

- The corrosion behavior of all the materials tested was relatively insensitive to mildly flowing seawater but severe jet impingement reduced the corrosion resistance drastically for the 316 L and 430 alloys.

- The study indicated that the corrosion behavior of titanium, the super austenitic stainless steel and the nickel base alloy was not were not sensitive to an increase in salinity. In contrast the higher salinity water was more aggressive towards the lower alloyed materials.

“Performance of High Chromium Stainless Steels and Titanium Alloys in Arabian Gulf Seawater” (Odwani, Al-Tabtabaei and Abdel Nabi 1998)

Odwani, Al-Tabtabaei and Nabi discuss a study which was performed to assess the sustainability of certain alloys for seawater applications. Electrochemical impedance spectroscopy was employed to evaluate the corrosion performance of four high chromium stainless steels and grade 2 titanium in natural flowing Arabian seawater.

- The test specimens were exposed to the filtered seawater feed at the Desalination Research Plant Doha in Kuwait for 3,000 hours. Temperatures ranged between 20°C and 30°C with a pH of 6.5-7, and a flow rate of 100 L/min.

- The study demonstrated the beneficial effects of raising Cr, Mo and N contents on the localized corrosion resistance of stainless steels in seawater at ambient conditions.

- Stainless steels 316 L and 317 L performed poorly compared to the other materials studied. Stainless steels 317 LMNO and 254SMO and Ti(2) performed well and gave no signs of corrosion attack.

"Copper Nickel Alloys for Marine Applications" (Powell and Jenkins 2000)

Powell and Jenkins review and summarize the history of the use of copper and copper-nickel alloys in marine applications.

- Copper and copper-nickel alloys have been used in numerous marine applications throughout history. Some of the main applications of copper and copper-nickel alloys include sheathing and hull construction, fasteners and hardware, piping systems, and heat exchangers.

- Offshore structures have been clad in highly corrosive zones using nickel-copper alloy 400 and copper-nickel alloy C70600. There is significantly less fouling of the cladding than of bare or coated steel and the fouling can be removed much more easily.

- The corrosion resistance, bio-fouling resistance, heat conductivity, and ease of fabrication of these alloys make them a viable option in traditional and innovative marine applications.

"Corrosion Behavior of High-Nickel and Chromium Alloys in Natural Baltic Seawater" (Birn, Janik-Czachor, Wolowik and Szummer 1999)

Birn, Janik-Czachor, Wolowik and Szummer investigate the effects of Cl^- ion concentration and temperature on the stability of the passive state of high nickel and chromium alloys in both neutral and acidic electrolytes.

- The corrosion resistance, bio-fouling resistance, heat conductivity, and ease of fabrication of these alloys make them a viable option in traditional and innovative marine applications.

- Seawater experiments were conducted in a Polish research station at the Baltic Sea. Samples were mounted in a tube where seawater flowed at a rate of 0.062

m/s. Free corrosion potential was measured and monitored during exposure. Samples were then removed from the water, cleaned and submitted to surface analytical investigations.

- The anodic behavior of the alloys tested appeared to depend mostly upon Mo content.

- All alloys tested were highly resistant, undergoing pitting corrosion only at elevated temperatures, at high anodic potentials, and at chloride concentrations higher than 1 M. No tendency to pitting was observed in the natural Baltic seawater. The alloys may have undergone crevice corrosion after prolonged exposure.

- Microscopic and surface analytical tests were performed to correlate the anodic and corrosion behavior of the materials with their composition and structure. Auger electron spectroscopy revealed that Mo was depleted within the passivating film formed on the alloys in the Baltic Sea. This points to the fact that Mo is not just like that of a passivity promoter, but rather it increases stability of the passive state as a dissolution moderator.

"Fatigue Crack Propogation in High Strength Steels for Use Offshore" (Billingham and Laws 1994)

Billingham and Laws examined the influence of alloy composition and microstructure on fatigue crack growth behavior of a number of welded high strength microalloyed steels intended to cover both existing and likely developments in offshore structures.

- The influence of applied cathodic protection levels on the corrosion fatigue crack propagation behavior of the selected steels was determined. The fatigue properties of welded high strength steels in synthetic seawater were found to decrease as the applied cathodic potential is decreased. Potentials more negative than 950 mV should be avoided.

- At high negative overpotentials all steels showed significantly greater corrosion fatigue crack propagation rates compared to steels protected at -800 mV. Growth rates an order of magnitude faster were measured in some cases.

- Although there were differences in performance between the various steels tested, no direct relation was identified between special microstructure or compositional features and improved fatigue performance. Even with the care taken in welding the samples, the crack tip often sampled a variety of microstructures throughout the duration of the fatigue test.

“Materials Selection for Pitting and Crevice Corrosion” (Ylasaari, Forsen, Aromaa, and Virtanen 1997)

Ylasaari, Forsen, Aromaa, and Virtanen review steel selection methods for the process industry. Experiments were performed to determine the effects of alloying elements and microstructure on pitting and crevice corrosion.

- PRE-values calculated from the composition of steel can be used as a first estimate on the corrosion resistance but no general relationship exists between solution corrosivity and material corrosion exists. An accurate method for determining corrosion resistance could be the compilation of pass-fail charts in log[X^-]-T domain based on cyclic polarization curves; where [X^-] is the concentration of an aggressive anion.

- Cyclic polarization experiments were performed on three austenitic and three duplex stainless steels chosen for their corrosion resistance. The tests solutions were simple ammonium chloride and DIN 50900 seawater.

- The results of polarization tests were used to construct pass-fail charts for the tested materials at different temperatures and chloride contents. The criteria for a “pass” result was no hysteresis loop and no visible pitting or crevice corrosion.

- Stainless steels S31254 and S32750 exhibited the best pitting corrosion resistance followed by S31726.

“Overview of Metallic Materials for Heat Exchangers for Ocean Thermal Energy Conversions” (Kapranos and Priestner 1987)

Kapranos and Priestner review candidate materials for use in ocean thermal energy conversion heat exchangers, including aluminum, copper-nickel, stainless steel and titanium alloys.

- The power system of an ocean thermal energy conversion system must be designed for a long life, up to thirty years, with minimal maintenance. Material selection must be based on corrosion and durability performance for the life of the project.

- Aluminum is attractive because of its low cost but its corrosion resistance in seawater is poor. Protective measures and frequent maintenance is required. An OTEC plant built from aluminum alloys would have an expected life of 10 to 15 years. Prime candidates for OTECS applications are alloys 5050, 5052, 6061 and 6063.

- Copper-nickel alloys are commonly used in power plants and perform well in seawater condensers. For OTEC applications the prime candidate is alloy CA 706.

- This alloy has maintained design heat transfer efficiency for long periods with out water treatment or mechanical cleaning. CA 706 has excellent antifouling properties.

- Alloy AL-6X (2Cr-25Ni-6Mo) is the only alloy that has been qualified for OTEC heat exchangers. It is used in numerous power plants for seawater cooling and has comparable performance with titanium alloys. Austenitic stainless steels perform well in seawater as long as their surfaces are clean, but once crevices form, attack is very rapid. Ferritic stainless steels are strong possibilities due to their excellent resistance to pitting and crevice corrosion. Leading candidates include Fe-29Cr-4Mo and 26Cr-3Mo-2Ni.

- Although the initial cost of titanium is high, maintenance and replacement costs are minimized. Most titanium alloys being considered are commercially pure such as Ti-50, ASTM Grade 2. Ti-Pd alloy (Grade 7) and Ti-Code-12 alloy (Grade 12) are alternative alloys offering better corrosion resistance.

"Performance of OTEC Heat Exchanger Materials in Tropical Seawaters" (Larsen-Basse 1985)

Larsen-Basse discusses the results of a three year study of corrosion involving several aluminum alloys in flowing surface seawater and 600 meter deep cold seawater.

- The closed cycle OTEC concept consists of a working fluid which evaporates in a heat exchanger by warm surface water at 25-30º C and drives a turbine to produce power, and then is condensed in another heat exchanger by deep ocean water at 5-8º C.

- A more cost effective alternative to titanium and high-alloy stainless steels, while maintaining immunity to corrosion, is desired for OTEC projects. Copper-nickel alloys would probably be ruled out due to their susceptibility to attack by the ammonia working fluid.

- Alloys 5052 and Alcad (7072) 3003 were chosen, based on evaluation of the available corrosion data, for testing in the warm surface water and cold deep water in Hawaii. In the warm water corrosion was rapid during a short initial period and then leveled off to a rate of about 3 μm/year. This low rate is due to a thin inorganic scale film forming on the surface. The film consists of scale minerals precipitated from the seawater and aluminum corrosion products. In the cold, deep ocean water, all the alloys tested pitted, although they did not penetrate the cladding. The pitting tendency increased greatly as flow rate decreased.

“Ocean Thermal Energy Conversion – Materials Issues” (Darby 1984)

Darby reviews biofouling and corrosion studies of candidate alloys for OTEC heat exchangers. The biofouling experiments consisted of two parts, one to measure the rates of increase of the thermal resistance in certain alloys due to microfouling in seawater at possible OTEC sites, and the other to evaluate chemical and mechanical methods to minimize or eliminate the effects of fouling.

- The initial biofouling tests were carried out in Wrightsville Beach, N.C. at the LaQue Center for Corrosion Technology with further tests being carried out at the Seacoast Test Facility, Keahole Point, Island of Hawaii. The experiments showed that chemical cleaning by chlorination is the most promising for OTEC applications.

- Results showed that titanium and stainless alloy tubes can be kept fouling free with a minimum of 70 ppb level of chlorination for one hour per day. For aluminum alloys 5052, Alcad 3003, Alcad 3004, and bare 3003 required chlorination levels were slightly higher at about 100 ppb for one hour per day.

- Copper-base alloys were eliminated from further consideration as heat exchanger materials due to their susceptibility to erosion attack when exposed to ammonia, which is the best working fluid for a closed cycle OTEC plant.

- Of the stainless steels tested alloys 29-4C and Monit appeared to be the most resistant. Al-6X and SC-1 also appeared to have adequate resistance to crevice corrosion in an OTEC plant.

- Titanium has consistently shown no substantial corrosion in seawater, commercial heat exchanger practice, in the presence of ammonia, or under the influence of abrasive cleaning.

- Aluminum alloys tested showed no pitting in warm surface water. Initial corrosion in warm surface water is rapid after which a low rate of 3 μm/year was observed for all alloys tested. Results in cold seawater are inconclusive.

“Corrosion of Ferrous Alloys in Deep Sea Environments” (Venkatesan, Venkatasamy, Bhaskaran, Dwarakadasa and Ravindran 2002)

Venkatesan, Venkatasamy, Bhaskaran, Dwarakadasa and Ravindran study the corrosion of ferrous alloys at a variety of depths in the Indian Ocean.

- Five low alloy steels were chosen and exposed by attaching to a deep sea mooring at depths of 500, 1200, 3500 and 5100 m for 174 days. Specimens were also exposed off the coast of Gujarat at a depth of 3 m for 68 days. After removal the specimens were chemically cleaned and the corrosion rates were calculated. The surface morphology of the specimens was then observed.

- The corrosion rate of the 500 m deep specimens was the most severe followed by a large drop off for the 1200 m deep specimens and a gradual increase of corrosion rate to 5100 m depth. The increasing corrosion rate from 500 m to 5100 m depth correlates with the linear increasing dissolved oxygen between these depths due to the fact that oxygen is an effective cathode depolarizer.

- Atomic absorption spectroscopy of the materials shows that the corrosion product present on the mild steel was FeOOH. The morphology of the corrosion product revealed no protective film and the surface of the corrosion product was sufficiently porous for corrosion to proceed unhindered.

- In shallow water micro and macrobiological growths played a significant role in the corrosion of the ferrous materials. In deep water corrosion was not related to any biological product but mainly to the electrochemical reaction of these alloys with sea water. The corrosion rates of all five low alloy steels tested was about four times less in deep water than in shallow water.

"Nickel Base Alloys and Newer 6Mo Stainless Steels Meet Corrosion Challenges of the Modern Day Chemical Process Industry" (Agarwal 2001)

Agarwal reviews the various nickel alloys developed in the last 100 years and comments on future uses for the alloys developed in the last 20 years.

- Nickel and nickel alloys have useful resistances to a wide variety of corrosive environments that are often to severe for other commercially available materials.

- Nickel is very resistant to chloride stress corrosion cracking but can be susceptible to caustic cracking in aerated solutions in severely stress conditions. Under stagnant or crevice conditions severe pitting can occur. Nickel has a high thermal and electrical conductivity and a low vapor pressure.

- Alloy 400 has many advantages to commercially pure nickel; the addition of iron significantly improves the resistance to cavitation and erosion. Alloy 400 is used in conditions of high flow and erosion as in propellers, shafts, casings, condenser tubes and heat exchangers. Its corrosion rate in flowing seawater is generally less than 0.025 mm/year. Alloy 400 is generally immune to stress corrosion cracking.

- Alloy K-500 is the age hardened version of alloy 400 with benefits such as improved strength and hardness. This alloy is primarily used in marine and oil and gas applications.

- Alloy 825 is a modification of alloy 800 with the addition of molybdenum, copper and titanium for providing improved aqueous corrosion resistance.

- The 6Mo nickel alloys have increased molybdenum content and the addition of nitrogen to improve localized corrosion resistances. The 6Mo alloys have extensive uses in marine and offshore applications.

- Out of the “C” family alloy 59 has the highest chromium plus molybdenum content and the lowest iron content. It has one of the highest allowable stresses and great corrosion resistance. Alloy C-276 remains the most used and commercially available of the “C” family. The “C” family is used in a variety of marine applications.

“Deep Water Corrosion Fundamentals” (Jenkins and Mishra 1999)

Jenkins and Mishra review the differences between the deep water and sea-level environments and the influence of these environments on the behavior of materials.

- The characteristics of the marine environment that damage materials can be grouped into three broad categories, physical, chemical, and biological.

- The high electrical conductivity of seawater promotes the electrochemical reactions that are responsible for all types of corrosion. The temperature of the environment has several effects on corrosion as well; increasing the temperature increases the conductivity of seawater. Also, a temperature increase of 10° C commonly doubles the rate of diffusion, which is a limiting factor in many corrosion reactions. Temperature also increases the dissolved oxygen content of seawater, which has different effects on the corrosion rate of different materials.

- Ocean currents affect the corrosion rate of metals directly through the effects of velocity and indirectly by bringing ocean masses with varying chemical characteristics.

- Ocean structures extending through the tidal zones illustrate the effects of the environment on corrosion and the interaction between materials exposed to different environments. In the splash and spray zones, the distribution of sea salt and the high availability of oxygen can cause high corrosion rates. In the intertidal zone, corrosion rates are often low due to the oxygen concentration cell between the intertidal zone and the fully immersed zone. If the structure is steel the intertidal zone will be cathodic to the steel in the fully submerged zone.

- Biological organisms can affect materials physically; the film of organisms that attach to surfaces in marine environments inhibit diffusion and can damage protective coatings. Barnacles can create differential cells that cause crevice corrosion. Sea urchins “graze” metal surfaces removing corrosion products that normally inhibit corrosion.

- Oxygen content is an important factor in the stability of passive oxide films that are important in the performance of materials such as stainless steels and aluminum alloys. The solubility of oxygen varies inversely with temperature.

- There is no standard set for the depth at which the deep ocean environment starts. Jenkins has suggested that due to the dramatic changes in the accumulation of fouling organisms in the disphotic zone, the ocean environment should begin there, at 80 m depth.

- Oxygen content varies with depth. Typically the oxygen content is at a maximum at the surface and then decreases to a minimum at about 700 m depth. However, at warm sites, the surface oxygen is lower and below the oxygen minimum zone can actually increase above levels at the surface.

- If the oxygen content is known, the corrosion behavior can be predicted, even without a thorough understanding of the processes involved.

- The number and types of organisms found in deep water are very different from those found in near-surface waters. There are far fewer macro-organisms in deep water and most of these live near the bottom sediments feeding on accumulated detritus.

- The possibility of corrosion is controlled by thermodynamics and the rate of corrosion is controlled by kinetics. The thermodynamics of a reaction are dictated by the half-cell reactions. The standard half-cell potential is a constant for an electrochemical reaction at a given temperature. These factors do not change in deep-water conditions.

- Under deep-water conditions, ionic concentrations are expected to be very low due to the enormous solvent volume. Such a decrease will cause regions of passivity to shrink on the Pourbaix's Diagram, and thus corrosion is more likely. However, a decrease in temperature will cause the regions of passivity to expand. Also water stability regions on the Pourbaix's Diagram expand with increasing depth.

- There are three ways to combat corrosion in the deep-sea environment; material selection, cathodic protection, and non-metallic organic coatings. Three sacrificial anodes are used in marine cathodic protection, Zn, Al, and Mg. However, impressed current cathodic protection is more commonly used in the deep-sea environment. Organic coatings are the most commonly used form of corrosion protection with the other two methods being used as back up.

- 5 mA/ft^2 current-density is required to protect bare steel in quiet seawater. A 12 lbs zinc anode can protect 100 ft^2 of steel for 14 months. A good vinyl paint can reduce the current requirements five-folds.

- It is all but impossible to maintain 100% integrity in any organic coating. Metals that have noble solution potentials cause intensified attack of active unalloyed steel or aluminum.

- Anti-fouling coatings work by continuously releasing toxins at a low rate. Typical toxins used for deep-water protection are cuprous oxide and tributyl tin oxide. Coating thickness for deep ocean structures is usually around 0.015 in.

- High strength welded structures are very susceptible to hydrogen damage. The use of cathodic polarization to prevent corrosion of steel in underwater service influences the hydrogen ion discharge on the metal surface. Hydrogen damage depends on the type and severity of loading. A static tensile load is typically required for hydrogen cracking of steel.

- Aluminum alloys depend on an oxide film for corrosion resistance; their rate of pitting depth increases as oxygen and pH decrease. Copper alloys have a low corrosion rate which varies little with depth. Nickel alloys are also unaffected by depth; alloys that are susceptible to crevice corrosion remain susceptible at any depth. Steels have a dramatic reaction to increasing depth in that their performance decreases with increasing oxygen content. Stainless steels show a minimal effect of depth on corrosion. Some alloys show a reduction in propagation rate. Titanium alloys show no corrosion at any depth.

- Non-metallic materials are also affected by exposure to both shallow and deep-water ocean environments with biological activity being the primary cause for deterioration. Ceramics are resistant to corrosion at nearly neutral pH and may be used in deep-water if loaded in compression.

"Biofilm Effect on the Cathodic and Anodic Processes on Stainless Steel in Seawater Near the Corrosion Potential: Part 1 – Corrosion Potential" (Salvago and Magagnin 2001)

Salvago and Magagnin investigate the effect of biofouling on the corrosion potential during exposure to seawater and use a statistical approach to characterize the enoblement of the corrosion potential.

- Ennoblement of the corrosion potential for passive metallic materials takes place during exposure to natural biotic seawater below 30° C. Biofilms formed on stainless steels after immersion in natural waters, in the abence of localized corrosion, raise the corrosion potential from initial values below 0 mV to values from 300 mV to 500 mV.

- The corrosion potential evolves with time and its increase raises the likelihood of localized corrosion. The depolarization of the cathodic process, caused by the development of the biofilm, is the cause of the greater aggressiveness of biotic waters compared to abiotic ones.

- UNS S30400 and S31600 coupons were exposed to constant turbulent seawater for one month. Each coupon's corrosion potential was measured and recorded every six hours. At the end of the month the specimens were cleaned and microscopically examined.

- Of the S30400 coupons 37 of the 48 showed signs of crevice corrosion. The corroded coupons also showed large amounts of biofouling.

- Localized corrosion manifests itself through steps of initiation, repassivation and propagation phenomena. The corrosion potential mean value of the corroded specimens was lower than the corrosion potential mean value of the uncorroded ones.

- Much experimental evidence considered to be caused by the microbial activity at the passive metal surface can be justified without enhancement of the cathodic process. Small shifts in the theoretical polarization curves could be enough to cause large variations of the corrosion potential in passive conditions and could justify the ennoblement of the corrosion potential.

"Long-Term Ennoblement Studies On Ni-Cr-Mo Alloys" (Martin, Lemieux, and Natishan 2006)

Martin, Lemieux, and Natishan present work that demonstrates how corrosion potential ennoblement can persist during long-term seawater exposures for several Ni-Cr-Mo alloys. The implications of this ennoblement are discussed.

- Seawater corrosion potential ennoblement can occur in passive alloys that are resistant to seawater pitting but are poor oxygen reduction surfaces. This manifestation can cause corrosion potentials in excess of 300 mV. The biofilm-derived electrochemistry provides an alternate oxygen reduction pathway on passive film surfaces and is linked to increased localized corrosion in passive metals.

- It was found that ennoblement biofilms can adapt somewhat to cathodic demand. The time required for this adaption is similar to the time required for development of ennoblement.

- Ennoblement-driven corrosion potentials were shown to last the two year duration of the test. Open circuit potentials dropped every morning at sunrise, confirming that sunlight has a mitigating effect on ennoblement.

- All long-term ennoblement exposures showed at least a doubling in cathodic current capacity when galvanically connected.

- Ennoblement creates an increased capacity to drive galvanic or localized corrosion at potentials above -400 mV but a decreased capacity to support such corrosion at potentials below this.

- It was shown that ennoblement-derived corrosion potentials are similar to crevice corrosion initiation temperatures in alloy 625.

“The Behaviour of Corrosion-Resistant Steels In Seawater” (Bardal, Drugli and Gartland 1993)

Bardal, Drugli and Gartland review research on localized corrosion occurring on stainless steels in seawater.

- When temperatures are less than 40° C, stainless steel exposed to natural seawater develops a biofilm which stimulates the cathodic reaction. This causes the potential to rise to 300 to 400 mV in just a few days and acts to raise the risk of localized corrosion initiation; in some cases drastically.

- The cathodic current density of stainless steel polarized to -100 to +100 mV is a very sensitive indicator of the bioactivity occurring on the surface.

- In chlorinated seawater the potential of non-corroding stainless steel rises even higher than in natural seawater, around 500 to 650 mV. Therefore the risk of localized corrosion is increased. However, the cathodic efficiency is much lower in chlorinated seawater. Thus, the propagation rates will be under cathodic control unless there is a very large cathode to anode area ratio.

- During the period where the open circuit potential is rising, susceptibility to localized corrosion is at a maximum. After a long exposure time in chlorinated seawater stainless steels become more resistant to localized corrosion.

- A potentiostatically controlled critical temperature test is suggested to establish a design curve for maximum operating temperatures for a given stainless steel in seawater-like solutions.

- There is a critical temperature at which crevice corrosion begins to initiate and a lower critical repassivation temperature.

“A High Strength, Corrosion-Resistant Alloy Solves Fastener Problems in the Marine Industry” (Hibner and Shoemaker 2004)

Hibner and Shoemaker discuss the use of Inconel alloy 686 as a high strength, highly corrosion resistant fastener in the marine industry.

- Because of the size and working environment of marine fasteners, they must be very corrosion resistant in order to resist the effects of galvanic and crevice corrosion, and because they are often anodic to the surrounding structure. Thus, corrosion-resistant nickel based alloys have been used extensively in the marine environment.

- Monel K-500 alloy fasteners are commonly used with steel in seawater environments, but the resulting galvanic coupling can induce hydrogen charging and cause embrittlement of the fasteners.

- Inconel alloy 686 is a nickel-base alloy that exhibits high tensile strength and fracture toughness, as well as excellent corrosion resistance in the marine environment. It achieves this excellent performance by containing a unique combination of chromium, molybdenum and tungsten.

- Alloy 686 exhibits excellent high cycle fatigue behavior in seawater. Its critical crevice temperature was found to be greater than 85° C in an acidified 6% ferric chloride solution (ASTM G48 C & D). It outperforms nickel alloys C-276, 725 and 625 in localized corrosion resistance. Also, alloy 686 was found to be galvanically compatible to alloys 625, 400 and K-500. Alloy 686 is highly resistant to hydrogen embrittlement.

- Alloy 686 is a solid solution strengthened, single phase, austenitic alloy. It exhibits a fracture toughness of over 350 MPa($m^{1/2}$) and an impact strength of 133 N-m. It is cold workable to a yield strength of over 1000 MPa.

"Predicting Localized Corrosion in Seawater" (Srindhar, Brossia, Dunn and Anderko 2004)

Srindhar, Brossia, Dunn and Anderko develop a model based for the calculation of repassivation and corrosion potentials.

- A methodology was developed to predict the long-term occurrence of localized corrosion in seawater by comparing values of passivation and corrosion potentials for several different alloys. A mechanistic model has been established to determine corrosion potentials and an empirical model has been established to determine repassivation potentials.

- The model and experimental results show that the corrosion potential of Type 316L stainless steel is typically more positive than its repassivation potential in seawater. This results in localized corrosion of the alloy. Chlorination further increases the corrosion potential and exacerbates the corrosion.

- Conversely, the corrosion potential of alloy 254SMO in natural seawater is more negative than its repassivation potential. Thus it is expected to be resistant to localized corrosion.

- Like alloy 316L, the corrosion potential of Al 1100 in natural seawater is more positive than its repassivation potential and consequently aluminum would be expected to suffer localized corrosion.

“Corrosion of Weathering Steels” (Fletcher 2005)

Fletcher reviews the types, uses and performance of weathering steels.

- Weathering Steels contain specific additions of alloying elements to increase their resistance to atmospheric corrosion. The essential feature of weathering steels is the development of a hard, dense, tightly adherent, protective rust coating on the steel when it is exposed to the atmosphere. Weathering steels have significantly reduced corrosion rates in the atmosphere compared to carbon steels.

- Weathering steels came into being in the early 1900’s when it was discovered that copper-bearing steels with more than 0.15% Cu provide a 50% improvement in service life. The formation of a protective rust film results in deceleration, but not cessation, of corrosion.

- The atmospheric corrosion of iron and steels is a function of the composition of the steel, environmental conditions, characteristics of the rust layers, cyclic wetting and drying periods and contamination by particulates. Elements that promote atmospheric corrosion resistance include phosphorus, silicon, chromium, copper and nickel and to a lesser degree carbon, molybdenum and tin.

- If goethite formation is inhibited by excessive periods of wetness, weathering steel does not develop a protective rust, and corrodes rapidly. Weathering steels should only be used when yearly average time of wetness is less than 60% and when chloride levels are less than 0.5mg/100 cm^2 * day.

“New Technology Stainless Steels and Nickel Alloys for Marine Applications in the Year 2000 and Beyond” (Ross 2000)

Ross reviews new developments in nickel and stainless steel alloys in the marine industry.

- There are five main types of stainless steels ferritic, martensitic, austenitic, precipitation hardening, and duplex. Most ferritic and martensitic stainless steels have limited corrosion resistance in seawater, except for some of the new super ferritics. Austenitic stainless steels are iron-chromium-nickel alloys. Through additions of molybdenum and nitrogen they can achieve excellent corrosion resistances. The precipitation hardening stainless steels are nickel-chromium-iron alloys that have higher strength than the austenitics but have less ductility and are more susceptible to corrosion. The duplex stainless steels are iron-chromium-nickel alloys that contain a 50-50 mix of ferritic and ausenitic crystal structures. The strength of duplex stainless steels is roughly twice that of common austenitic stainless steel. Many duples stainless steels have excellent resistance to corrosion in the marine environment.

- In the 1940's nickel chromium alloys entered the marketplace. Around the same time additions of iron and molybdenum were being experimented with. The resulting alloys were used in a variety of chemical plants. Additions of Ti, Al, W, and Nb to the nickel alloys yielded high strength alloys, the first of which was K-500. In recent years several high strength nickel alloys have been developed for marine use, including 718, 625, 725, and 925. The most corrosion resistance family in the marine environment is the C family, which have 16-24% Cr and 14-16% Mo. Alloys C-4, C-276, C-22, 686 and 59 comprise this group.

- Corrosion is a surface phenomenon and the condition of the surface of the stainless steel or nickel alloys may have a significant effect on its performance. The corrosion resistance of the alloys is provided by a thin, invisible, passive film on the surface. If the passive film is continuous and remains stable, the alloy will resist corrosion. If the film is not continuous localized corrosion in the form of pitting or crevice corrosion may initiate and propagate rapidly. Embedded iron and heat tinting are two common surface defects that can result in reduced corrosion resistance. Care must be taken to prevent their formation.

- Types 304 and 316 stainless steels have adequate corrosion resistance for many mildly corrosive marine applications. However some applications require more corrosion resistance. Stainless steels with a PREN greater than 40 are generally considered to be very corrosion resistant in most marine applications.

- Crevice corrosion resistance is frequently the limiting factor for stainless steels in marine service. Duplex alloys with a PREN over 40 are highly resistant to crevice corrosion. They are also more resistant to chloride ion stress corrosion cracking than austenitics.

- The cost of stainless steels is roughly proportional to their corrosion resistance. It is important to select an alloy with sufficient but not excessive corrosion resistance for this reason.

- Nickel alloy 400 has excellent corrosion resistance as long as the seawater is not stagnant. In cases where more corrosion resistance is required, nickel alloys with a PREN greater than 50 show excellent resistance to crevice corrosion. Nickel alloys are highly resistant to hydrogen embrittlement and stress corrosion cracking. They also show much better corrosion fatigue resistance than the austenitic stainless steels.

“Understanding Material Interactions in Marine Environments to Promote Extended Structural Life” (Shifler 2005)

Shifler discusses parameters that affect material performance in marine environments and suggests way to protect certain alloys.

- There are two processes operating simultaneously in the seawater environment: formation and repair of passive films on alloy surfaces due to the presences of dissolved oxygen, and breakdown of passive films due to chloride ion activity.

- The performance of a material in a marine environment depends on the service parameters, choice of materials, corrosion control methods, the type of environment and design configurations.

- The main factor controlling the corrosion rate of an alloy is the passive film. There are four ways a metal may passivate in aqueous solutions: the air-formed film, a salt film, chemisorption of the solvent, and an oxide formation. The formation of passive films reduces ionic transport of reactive species causing corrosion. The breakdown of passivity is associated with a critical potential, the presences of aggressive species and discrete areas of attack.

- Physical and mechanical properties of materials influence the way passive films resist corrosion. Thermal expansion can cause surface films to tear. Hydrogen can enter many ferrous alloys and promote degradation. The susceptibility of high strength steels to hydrogen is related to their tensile strength and the binding energies of specific trapping sites.

- Failure of fasteners can occur due to environmentally assisted cracking resulting from applied stresses and hydrogen embrittlement. Weld joints have three different zones: the cast weld zone, the heat affected zone, and the parent metal. Welding defects can have a dynamic effect on the corrosion resistance of welded joints.

- Corrosion rate in seawater is dependent upon temperature, oxygen content, salinity, water chemistry, pH, biofouling, pollution, galvanic interactions, fluid velocity, alloy composition, alloy surface films, geometry, surface roughness, and heat transfer.

- Generally, corrosion increases as temperature increases. The degree by which dissolved oxygen influences corrosion is dependent on the alloy. Oxygen is favorable for passive film forming alloys, however, in fully aerated water, surface deposits on passive film-forming alloys can create oxygen concentration cells, which can cause pitting or crevice corrosion. For iron and steel corrosion increases with increasing oxygen content. Dissolved oxygen increases corrosion rates in copper alloys under fast flowing conditions.

- Biofilms can form environments on the surface of metals that are very different form the bulk fluid and may cause reactions not predicted thermodynamically. Biofilms cause a noble shift in open circuit potential of stainless steels, nickel, and titanium alloys. Biofilms are capable of increasing or decreasing corrosion rates.

- Fluid flow may increase corrosion rates by removing protective films or decrease corrosion by removing the build-up of aggressive ions. Geometry can have a significant effect on flow-assisted corrosion rates of metals. As pipe bend radii are reduced the corrosion rate will increase. The critical velocity at which corrosion becomes a problem in 90/10 Cu-Ni is 3.6 m/s for large pipe sizes and as low as 34% of this value for very small pipe diameters.

- Polluted waters contain hydrogen-sulfide and sulfate containing compounds, both of which are known to adversely affect the corrosion of some metals. Sulfide corrosion has been found to occur on a number of different copper-base alloys.

- The most common form of corrosion control is the use of coatings. The function of a coating is to provide an environmental barrier to the underlying material, preventing corrosion. Both organic and metallic coatings require good surface preparation in order to function properly.

- Corrosion is an electrochemical process and therefore electrode potential can be used to control the reaction rate. Cathodic protection is the most efficient and effective way to control corrosion for submerged alloys. Cathodic protection either employs a sacrificial anode, usually zinc or aluminum, or utilizes an impressed current to protect a structure. The electrochemical behavior of the cathode and anode are influenced by water depth, dissolved oxygen, temperature, salinity, pH, sea current, pressure and fouling. Coatings tend to distribute cathodic currents more uniformly. Cathodic protection causes the build-up of protective calcareous deposits which can lower current demand in natural seawater.

- Corrosion control involves preventing or delaying the onset of corrosion and minimizing its effects when it does occur. Materials selected should be compatible and be a part of an integrated plan that avoids compatibility problems. In some cases a compromise between mechanical properties and corrosion resistance may be required.

“Duplex Stainless Steels: Brief History and Some Recent Alloys” (Alvarez-Armas 2008)

Alvarez-Armas gives a brief history and some recent developments of duplex stainless steel grades.

- The mechanical strength of duplex stainless steels is very high. They may be used in many corrosive environments within the temperature range of -50 to 300 °C. Duplex stainless steels are far less susceptible to stress corrosion cracking as the austenitic 300 series. Duplex alloys are as resistant to pitting corrosion as austenitic alloys with similar PREN numbers.

- SAF 2507 has almost the same resistance to pitting and crevice corrosion resistance as 254 SMO, has twice the strength, and has a far lower cost.

- Austenitic stainless steels have good weldability and good toughness, but their stress corrosion cracking resistance and strength are comparatively poor. Ferritic stainless steels have good resistance to stress corrosion cracking but have poor toughness. Therefore a duplex stainless steel will have a proportional combination of these properties depending on the ratio of its austenite to ferrite structure.

- Recently the development of lean grade duplexes has lowered cost while retaining performance quality.

“Corrosion Resistances of Iron-Based Amorphous Metals with Yttrium and Tungsten Additions in Hot Calcium Chloride Brine: $Fe_{48}Mo_{14}Cr_{15}Y_2C_{15}B_6$ and W-Containing Variants” (Farmer, Haslam, Day, Lian, Saw, Hailey, Choi, Yang, Blue, Peter, Payer, Perepezko, Hildal, Branagan, Beardsley, and Aprigliano 2006)

Farmer, Haslam, Day, Lian, Saw, Hailey, Choi, Yang, Blue, Peter, Payer, Perepezko, Hildal, Branagan, Beardsley, and Aprigliano study the corrosion resistance of an iron based amorphous metal coating and the processes necessary to optimize pneumatic conveyance of the coating.

- In the metallic glass coating chromium, molybdenum and tungsten provide the corrosion resistance while boron enables the glass formation and rare earth metals such as yttrium lower the critical cooling rate. A low critical cooling rate enables the material to be rendered completely amorphous in practical materials processes. Rare earth metals do have the side affect of making pneumatic conveyance during thermal spraying difficult due to the powders having an irregular shape.

- SAM1651, also known as SAM7, has a critical cooling rate of approximately 80 Kelvin per second. SAM1651 has similar corrosion resistance to that nickel-based alloy C-22.

- Iron based amorphous metal coatings are very hard. SAM1651's hardness ranges from 1100-1300 VHN while the hardness of type 316L stainless steel is approximately 150 VHN and the hardness of alloy C-22 is approximately 250 VHN.

- Earlier developments of iron based amorphous metal formulations had non-optimal elemental compositions, were produced with non-optimal thermal spray parameters and exhibited rust after 13 cycles in the standardized salt fog tests. However SAM1651 is a pore-free thermal spray coating produced with improved amorphous metal formulations and shows no corrosion after more than 30 cycles in the salt fog test.

- It has been proved that iron based amorphous metals can be produced as either bulk alloys or coatings. The materials can be rendered as bulk alloys by using HVOF to form large plates on a flat mandrel.

"Corrosion-Resistant Metallic Coatings" (Presuel-Moreno, Jakab, Tailleart, Goldman, and Scully 2008)

Presuel-Moreno, Jakab, Tailleart, Goldman, and Scully describe recent studies on the corrosion properties of metallic coatings and examine the corrosion resistance of an amorphous Al-based coating.

- The attributes of metallic coatings can be tuned to deliver corrosion inhibiting functions by a selection of alloy compositions and nanostructures. Coatings can be made to function as a local corrosion barrier, serve as a sacrificial anode, and supply soluble ions used as corrosion inhibitors.

- In a coating containing active corrosion inhibitors defects may be protected over long distances by concentration gradient-driven random transport from inhibitor-rich regions. This distance is a function of the electrochemical properties of the sacrificial anode and the unprotected region. The electric field created by the galvanic couple between the coating and the substrate can be magnified in order to transport inhibitors large distances.

- By using metallic glass, elements can be mixed in a soluble liquid solution and then solidified at the transition temperature to achieve chemically homogenous solid solutions. Transition metals such as Co, Ni and Fe improve resistance to local corrosion while rare earth metals such as Ce, Y and serve as corrosion inhibitors when added as a salt in aqueous solution.

- Cathodic protection can be optimized by lowering the open circuit potential of the coating relative to the underlying substrate. It was shown that the Al-Co-Ce could be lowered as much as 750 mV below that of alloy 2024-T3 by altering the alloy composition and solution pH.

- Pulse thermal spray is one means of applying the coating system. It utilizes large quenching rates and results in a controlled particle size of 0.5 to 20 µm. Cold spray is another method of conveyance which utilizes the platic deformation of particles upon impact to achieve a uniform coating. Al-Co-Ce alloy coatings have been produced with thicknesses ranging from 75 to 600 µm with good adhesion and low porosity.

- A coating that can polarize an exposed substrate material a few hundred mV below its open circuit potential can lower its corrosion rate by a factor of 100 or more. This is accomplished by creating a galvanic couple potential below the localized corrosion threshold potential.

Appendix E

Literature Review of Optimization in Material Selection

“A Simplified Fuzzy Logic Approach for Materials Selection in Mechanical Engineering Design” (Sarfaraz Khabbaz, Dehghan Manshadi, Abedian and Mahmudi 2008)

Sarfaraz Khabbaz, Dehghan Manshadi, Abedian and Mahmudi introduce a simplified fuzzy logic approach to easily deal with qualitative properties of materials and the inherent fuzzy space. This enables a quick and reliable material selection to be made for engineering design.

- Material selection is a multi-criteria decision-making problem that involves trade-offs amongst decisive factors of material properties, manufacturing aspects, material cost, impact on the environment and availability.

- In this study fuzzy logic theory was used to select the optimum material for a function from a pre-ranked group of materials based on relevant properties. This pre-ranking of materials was done based on expertise knowledge.

- Fuzzy logic is a multi-valued logic which allows one to evaluate a set of variables by defining intermediate values between the conventional evaluation schemes such as true and false. It essentially enables computers a more human-like way of thinking. It requires the definition of fuzzy variables sets extracted from the physical problem.

- A fuzzy set is an expansion of the classical variable set between and including 0 and 1. A membership function is a function that defines how each element of the input space is assigned a value between 0 and 1. A fuzzy inference system is a framework that simulates the behavior of a given system using IF-THEN rules and is based off of expert knowledge or available data on the system.

- Rules are statements of knowledge that relate the compatibility of fuzzy premise propositions to one or more fuzzy spaces. In the case of a material selection the total number of rules is equal to the number of fuzzy sets raised to the number of material properties being considered.

- The weighted properties method (WPM) is a numerical method which ranks candidate materials on the basis of their performance indices. The Manshadi method is a numerical method used for material selection which combines non-linear normalization with a modified digital logic method. Both of these are compared to the fuzzy logic method of material selection, using the fuzzy toolbox of MATLAB, in three example material selections.

- The first case study was a material selection for a liquid nitrogen storage tank. Young’s modulus, density, thermal expansion, thermal conductivity, toughness, yield strength and specific heat were all deemed to be important material properties. Using three fuzzy sets yields a total of 2187 rules. Using the limiting logics simplification procedure a total of 14 logics were considered.

- Comparing the calculated material performance indices for case study 1, it is immediately evident that the fuzzy logic method is superior to the WPM method and very similar to the Manshadi method. The focal point is that the three materials rejected by the Manshadi method have performance indices more than half the value of the highest ranked material using the WPM method. The fuzzy logic method ranks the three worst performing materials less than one third the value of the best performing material.

- Similar results are obtained for case study two, material selection for a spar on an aircraft wing, and case study three, material selection for a cylinder mast on a sail-boat. In both of these cases the fuzzy logic method out performs the WPM method and compares well with the Manshadi method.

- The amazing thing about the fuzzy logic method is that is performs very similarly to the Manshadi method despite all its simplifications.

"A Web-Based Advisory System for Process and Material Selection in Concurrent Product Design for a Manufacturing Environment" (Zha 2004)

Zha reports on a method for selecting suitable manufacturing processes and material in concurrent design for the manufacturing environment. A fuzzy knowledge based decision method is proposed for multi-criteria evaluation and selection of possible manufacturing process/material combinations at the lowest total cost.

- In the development of a product designers will often conceive parts using processes and materials with which they are familiar. This often leads to the exclusion of more economic process material combinations.

- A manufacturing consulting service system uses the internet to bring together engineering reference material and acts as an informative educational tool. It includes basic process descriptions, special abilities, simple design rules, and links to fabrication websites. Its focus is on the trade-offs between the functional requirements of the part and that of manufacturing the part.

- The first step in selecting the best process and material combination is to assign a ranking method. The user enters design specifications for the requirements and then all process/materials are assigned a requirement rank, based upon the requirements value. These requirement ranks contribute to a weighting function.

- The kernel of the knowledge based decision support scheme is a fuzzy ranking algorithm. The fuzzy evaluation method works well due to the uncertainty of design specifications and technical requirements at the early conceptual design stage.

- A set of alternatives is defined as a fuzzy set for a given criteria to be evaluated. Then fuzzy ratings to the alternatives are defined as membership functions. The weights become fuzzy linguistic variables. The final fuzzy rating of an alternative can be characterized can be characterized by this membership function. An alternative with the highest membership function is the best option.

- Fuzzy ranking for evaluation and selection is more flexible and presents uncertainty better than more conventional methods. The designer can use linguistic ratings and weights such as “good”, “fair”, “important”, etc., for an alternatives evaluation and selection.

“A Decision Making Methodology for Material Selection Using an Improved Compromise Ranking Method” (Venkata Rao 2008)

Venkata Rao presents a logical procedure for the selection of materials for an engineering application. The procedure is based on an improved compromise ranking method that takes into account the material attributes and their importance to the application.

- The selection of an optimal material for an engineering design from two or more materials is a multiple attribute decision making problem.

- By utilizing fuzzy set theory the value of an attribute can first be described in linguistic terms, then converted into fuzzy numbers and finally to a score. An 11 point fuzzy numerical approximation system is presented in this work.

- The first step in the presented methodology is to identify the material selection attributes for the given engineering application. After deciding upon candidate alloys determine the best ($m_{ij\ max}$) and worst ($m_{ij\ min}$) values of all considered attributes.

- Next the attributes are weighted according to their relative importance using an analytic hierarchy process method. To accomplish this, a comparison matrix using a scale of relative importance is utilized.

- Assuming M attributes, the pair-wise comparison of attributes yields a square matrix A_{MxM}.

- The judgements are entered using a scale where a positive integer greater than one denotes a material attribute being more important than the one it is being compared with. The numbers 3, 5 ,7 and 9 correspond to the verbal judgements ‘moderate importance’, ‘strong importance’, ‘very strong importance’, and ‘absolute importance’. The numbers 2, 4, 6, and 8 are used for compromise between the previous values.

- In the reverse case, where a material attribute is deemed less important than the one it is being compared to, a reciprocal of one of the previous numerical judgments is assigned. The main diagonal of the matrix denotes each material attribute being compared with itself, and thus all be assigned values of unity.

- By doing this, in the matrix each material attribute is compared to each other material attribute twice, and the two numerical judgments assigned are reciprocals of one another. The row of the most important material attribute will be assigned judgments greater than or equal to 1, while the row of the least important material attribute will be assigned judgments less than or equal to 1.

- The normalized weight of each attribute is found be calculating the geometric mean of each row and then dividing these by the some of all the geometric means.

- A consistency ratio of less than 0.1 is considered to reflect an informed judgment that could be attributed to the knowledge of the analyst. The consistency ratio is found by dividing the consistency index by the random index.

- A performance index for each material is found by multiplying the difference between each material property value and $m_{ij\ max}$ (or oppositely, the difference between each material property and $m_{ij\ min}$ if a lower value denotes higher desirability for a given application) with its corresponding weighting, then dividing by $m_{ij\ min}$ subtracted from $m_{ij\ max}$, and then summing all the values obtained from each material property.

“An Intergraded Approach to Product Design, Materials Selection and Cost Estimation” (Farag and El-Magd 1992)

Farag and El-Magd propose an integrated approach to product design, material selection and cost estimation.

- As pressure to reduce product development time and cost increases, the need for an integrated approach of product design, materials selection and economic analysis also increases.

- Suggested is a step by step method to design and select materials for a project: 1) Perform the conceptual design and set the design objectives, 2) Identify the design limitations and failure criteria so that an optimum design range can be established, 3) Identify the material performance requirements, 4) Select candidate materials from a material database using performance requirements, 5) Generate optimum designs for each candidate materials, 6) Compare costs between each design-material combination, 7) Select the optimum design-material combination, 8) Commence detailed design.

“Data Systems for Optimal Material Selection” (Cebon and Ashby 2003)

Cebon and Ashby suggest a structured approach to achieve optimal material selections using data systems.

- Structured materials information is generated by statistically comparing the results of individual test records to determine minimum values of properties which can be reliably used for design purposes. Measured property values may then be combined to provide functional data, such as strength v.s. temperature.

- Optimal material selection requires two types of information; screening and ranking information and supporting information. The screening and ranking step requires a database of structured information to be filtered based on design requirements to yield a list of candidate materials. The supporting information step consists of searching through unstructured data with the purpose of narrowing the list of candidates to a few prime choices.

- The screening and ranking step is usually quantitative and consists of shifting through the database based on the technical and economic requirements of the design. The two types of selection criteria are constraints and objectives. Constrains are design requirements that must be satisfied, such as a minimum strength. Objectives are design criteria that must be maximized or minimized to optimize the performance of the component.

- The supporting information step is typically non-quantitative and is likely to contain specialist information. This may be information about the microstructure, details about joining characteristics, or corrosion resistance in a specific environment. Large quantities of information may be available and may be very detailed. This information should be found easily by entering keyword searches of candidate materials.

“Optimal Selection of Composite Materials in Mechanical Engineering Design” (Edwards, Abel and Ashby 1994)

Edwards, Abel and Ashby present a method for the optimal selection of composite materials based on performance indices, materials selection charts, and the use of bounds to define the envelope of properties accessible to a material.

- The performance of a structural component is a function of the functional requirements, geometry, and material properties. These parameters can usually be separated which makes the material selection independent from the details of the design.

- Typically performance depends upon two or more material properties which can be evaluated by plotting one material property on each axis of a materials selection chart. By superimposing the performance index on the chart an optimum choice of material can be made. Weighting factors can be applied as a means of compensating for the relative effect and importance of performance index groups.

- Material selection relies on a unique synergy of theory and practical experience.

"Multi-Objective Optimization in Material Design and Selection" (Ashby 2000)

Ashby explores the ways in which multi-objective optimization methods can be used to make optimal material selections.

- When choosing a material the goal is to optimize the metrics of performance in the product in which it is used. The difficulty is that the choice that optimizes one metric will not, in general, do the same for the others. It then becomes a compromise, trying to push all metrics as close to their maxima as their interdependence allows.

- The performance of a component is measured by performance metrics, which depend upon control variables that represent all properties of a material. Multi-objective optimization is a procedure for simultaneous optimization of several independent metrics.

- When there are two or more objectives they are usually measured in different units and in conflict with each other. If two objectives are plotted against one another there exists several points on the graph, representing materials, that have characteristics that no other solution exists with better values of both performance indices. These solutions are connected by a line or surface called an optimal trade-off surface.

- The trade-off surface identifies the materials that have the best compromise between the objectives, but it does not distinguish between them. One can either choose a solution using intuition or by formulating a value function. A value function is formulated by multiplying each objective by an exchange constant and then adding them all together. An exchange constant relates a performance metric to value measured in currency, that is they measure the change in cost for a unit change in a given performance metric.

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