



Modeling, Integration, and Automation of Degradation to Generate Asset Lifespan Analytics Using AssessLIFE Software

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ABSTRACT

The degradation of metallic industrial assets, equipment, and components costs governments, industries, and citizens billions of dollars a year. Also, the degradation of industrial assets and infrastructure proliferates myriad safety problems. AssessLIFE software addresses this strategic deficiency by focusing on forecasting strategies rather than on mitigation strategies in the active battle against industrial asset degradation. By employing tested and proven scientific analytical computations, forecasting, prediction, and analytics, the AssessLIFE software plans to significantly reduce the billions of dollars expended via inspection, treatment, and repair of degradation-prone assets and infrastructure. The AssessLIFE software leverages many scientific studies and research in many fields of engineering. The AssessLIFE software also emphasizes the computerization or automation of the processes of metallic (alloys and welds) degradation mechanisms and parameters using digital techniques.

KEYWORDS

Alloy Degradation, Atmospheric Corrosion, Corrosion, Corrosion Fatigue, Erosion, Fatigue, Flow Turbulence, Galvanic Corrosion, Intergranular Corrosion, Pitting Corrosion, Stress Corrosion Cracking

INTRODUCTION

ENVIRONMENTAL IMPACT OF ALLOY DEGRADATION

“The three main global challenges for the twenty-first century are energy, water, and air – that is, sufficient energy to ensure a reasonable standard of living, clean water to drink, and clean air to breathe. The ability to manage corrosion is a central part of using materials effectively and efficiently to meet these challenges” (Revie & Uhlig, 2008). AssessLIFE Software ties aptly into providing solutions to one of the biggest challenges facing humankind in the modern world, namely, the effective and efficient use of generated energy and the reduction of greenhouse gases released into the atmosphere.

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Premature failures of alloys in industrial assets typically involve the replacement of the failed assets with assets made of similar or dissimilar alloys. Since alloy production involves intense energy usage via high-temperature heating, which subsequently (in most cases) involves the release of greenhouse gases, the effective and efficient usage of industrial alloys and the minimization of premature failures directly reduces the level of greenhouse gases released to the atmosphere. Thus, AssessLIFE Software provides a means to select the right alloys for the right industrial applications to ensure that the alloys employed in industrial settings globally for the production of goods and services attain reasonable service-lives or lifespans and minimize the high risks of premature asset failures.

FINANCIAL IMPACT OF ALLOY DEGRADATION

Many of the world's physical infrastructure are made of alloys. Alloys are typically solid metallic substances produced by mixing chemical elements (called alloying elements) into a molten or a liquid metallic-based matrix before its solidification via cooling. In many cases, the alloying elements are employed to modify the properties of the metallic-base matrix. For example, the author Choudary (2003) explained that "the term 'alloy steel' is used to describe those steels to which one or more alloying elements, in addition to carbon, have been deliberately added in order to modify the properties of steel." Alloys, which constitute the materials of construction for a significant portion of the global industrial and manufacturing structures and assets employed in the production of goods and services, are expensive when compared with many other types of industrial construction materials such as wood, fiber glass, polymers, composites, and so forth.

Globally, billions of dollars per year are expensed in alloys and asset research, design, manufacture, procurement, fabrication, installation, and operations in applications that include infrastructural, military, industrial, machinery, aeronautical, automobile, residential, transportation, and astronomy. Unfortunately, these very expensive alloy-based assets, equipment, and components are constantly and relentlessly degraded by natural and man-made forces. With the passage of time (in some cases, a few short years), the alloys or assets lose their functions, degrade, and crumble into a useless pile of metallic junk. Unless these unrelenting degradation processes are actively combated, the huge funds expended in creating these assets will be and are wasted. Degraded infrastructure endangers personal safety, increases the cost of production of goods and services and production losses, maintenance cost overruns, and cost of insurance coverage. The degradation of metallic industrial assets, equipment, and components, costs governments, industries, and citizens billions of dollars a year. Unfortunately, most of the billions of dollars expended per year on the degradation of metallic components used in industrial assets and equipment are focused on mitigation strategies such as inspection, treatment, and repair – after the degradation is prone to occur or has already occurred.

Corrosion causes many problems for humankind. It damages equipment, structures, and the environment in the vicinity of corroded structures. Its cost ranges between 3.1 to 4.5% of the Gross Domestic Product (GDP) in industrialized nations. The annual cost of corrosion in the United States is approximately US\$300 billion. Canada spends 3.1% of its GDP, or CAN\$32.8 billion, on corrosion prevention and control. This amount, which quantifies only the direct cost of corrosion prevention and control, amounts to approximately two-thirds of the Canadian government's annual expenditure on health and education, twice the amount spent on research and development, and thrice the expenditure on national defense. It is estimated that 25% to 30% of the annual cost of corrosion could be saved with optimum corrosion management strategies (Obi, 2008).

Several research studies and industrial innovations have significantly improved preventive measures of corrosion, including coatings (Bahadori, 2015; Jones, 1996; Revie et al., 2008; Schweitzer, 2006; Winkelaar, 2009), cathodic protection (Cicek, 2013; Jones, 1996; Revie et al., 2008), and anodic protection (Cicek, 2013; Edeleanu, 1960). Coating prevents degradation by presenting typically non-reactive or inert barrier between the environment and the alloy. Typical materials used for coatings include nitrocellulose, alkyds, acrylics, polyurethanes, and epoxies (Winkelaar, 2009). Cathodic

protection involves suppressing corrosion reactions on an alloy by supplying the alloy with electrons from an external source. Cicek (2013) added that “cathodic protection simply involves supplying, from an external source, electrons to the metal to be protected, making it a cathode.” For alloys that generate insoluble oxide films in their exposed medium, anodic protection (Cicek, 2013) involves facilitating the production and maintenance of the insoluble films on the alloy, which thereafter accords the alloy protection in the medium. Scenarios occur where anodic protection is the most practical or economical options to minimize alloy degradation via corrosion. “In [a] chemical plant, it is often not economic to use noble metals, and if the solutions are highly oxidizing the other methods are inapplicable. In these scenarios, anodic protection is achieved by: (1) Using a metal having an oxide (or other similar corrosion product) which is virtually insoluble in the medium (2) ensuring that sufficient oxidizing agent is always present for the oxide to be formed, and (3) applying anodic polarization to maintain the oxide in the constant repair” (Edeleanu, 1960). However, one of the most effective methods to minimize the safety risks, economic wastage, and environmental contamination generated by alloy degradation is to select the proper alloys that can perform adequately within the specified exposure environment and to estimate as accurately as possible the lifespan of the alloys – beyond which they need to be replaced. In this way, premature failures (with all the attendant risks and consequences) are significantly minimized. In most cases, the most effective method of corrosion prevention is by proper selection of materials resistant to the specific corrosive environment (Jones, 1996).

It has been estimated that about 3.5% to 5% of an industrialized nation’s income or its Gross National Product (GNP) is spent on corrosion prevention and maintenance, or replacement of products lost or contaminated as a result of corrosion reactions, such as the rusting of the automotive body panels, radiator, and exhaust components. The British Hoar committee prepared a corrosion cost report indicating that corrosion costs 3% of British GNP, of which 23% can be prevented. Batelle Columbus Laboratories estimated the losses due to corrosion in U.S. equaling 4.9%, while National Bureau of Standards (NIST), found it to be 4.2%, and both with an error margin of $\pm 30\%$. Both studies revealed that a maximum of 45%, a minimum of 10%, and an average of 15% of the corrosion cost could be prevented. The cost of corrosion in the U.S. was about 3.5 to 4.5% of the country’s GNP, resulting in about 70 billion dollars of loss in 1976, which increased to 126 billion dollars in 1991. The percentage losses are even higher in underdeveloped or developing countries, where corrosion protection measures are not sufficiently implemented. However, in practice, it is generally accepted that only up to 30% of the corrosion loss can be prevented (Cicek, 2013).

ASSESSLIFE SOFTWARE: SIMULATING ALLOY DEGRADATION VIA THE MECHANISM OF WET CORROSION

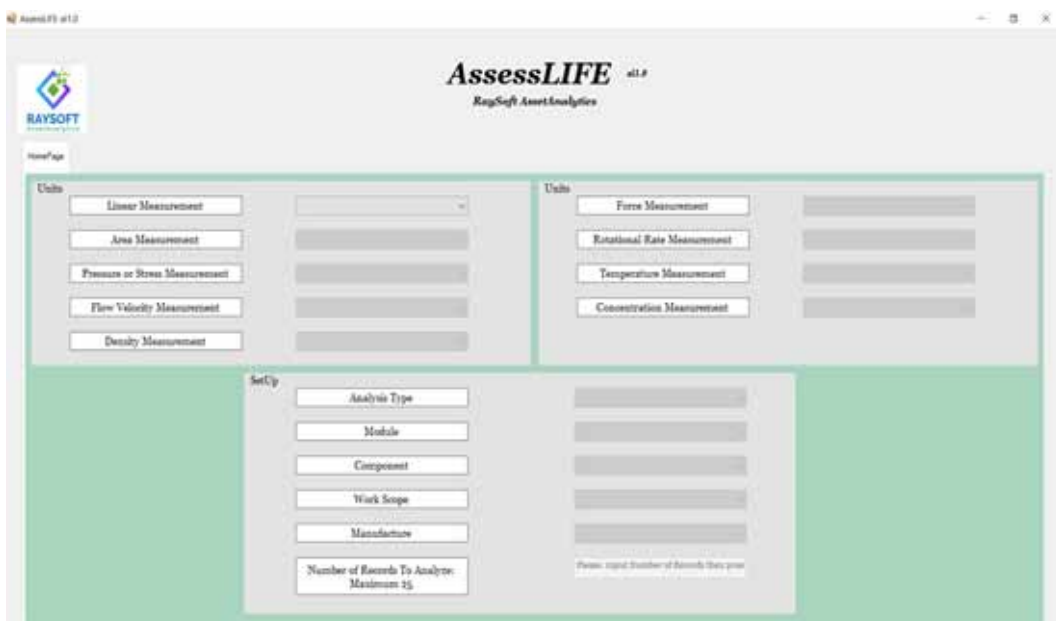
AssessLIFE software aims to select the proper resistant alloy for the defined exposure conditions as well as estimate the lifespan of the alloy during which the alloy provides adequate performance and, thereby, minimizes premature failures. Furthermore, AssessLIFE software addresses the strategic deficiency of employing trailing strategies such as inspections, treatments, and repairs. In addition to enhancing preventive strategies such as coating, cathodic and anodic protection, the AssessLIFE software, in the active battle against industrial asset degradation, focuses on forecasting strategies rather than on mitigation strategies. By employing tested and proven scientific analytical computations, forecasting, prediction, and analytics, the AssessLIFE software plans to significantly reduce the billions of dollars expended via inspection, treatment, and repair of degradation-prone assets and infrastructure.

Figure 1 shows the Home Page of the AssessLIFE software. Engineering units constitute the first set of entries into the software. In a sequence, the user is guided to enter all the relevant engineering units needed by the software. The “Setup” box, which is below the “Units” box, contains all the selection boxes where the user configures the software for analysis. The configuration boxes in the “Setup” domain guides the user to define all the major specific details that influence degradation and enables the AssessLIFE software select the appropriate as well as specific computational

methods with which to process user input data. The user enters both the asset identifier data and the field data downstream of the Home Page. The configuration boxes in the “Setup” domain include: “Analysis Type”; “Module”; “Components”; “Work Scope”; and “Manufacture.” The entry box “Number of Records to Analyze: Maximum 25” (shown in Figure 2) completes the software high-level configuration. The user enters an integer that defines the number of records of assets that will be analyzed. Each entry of the high-level selection boxes helps define a specific use scenario that the software will simulate and analyze. Furthermore, the options selected for each of these high-level configuration boxes progressively defines the downstream user interface pages and the control boxes on these pages that are presented to the user for data entry.

Figure 3 shows the dropdown list for the “Analysis Type” options of the AssessLIFE software. The options include “Wet Corrosion,” “Atmospheric Corrosion,” “Corrosion Under Insulation,” “Erosion,” “Wet Corrosion + Erosion,” “Metal Fatigue (via rotating element),” and “Corrosion Fatigue (via rotating element).” The options within the “Analysis Type” configuration box define the major degradation mechanisms that drive the failure of industrial assets or alloys. In Obi (2008), corrosion is depicted as the degradation of a material by electrochemical or chemical reaction with its environment. Wet corrosion occurs when the mobile ions (or atoms or groups of atoms with a resultant charge) from electrochemical or chemical reactions move within a liquid medium and interface with electrons confined to the metallic structure of the alloy(s). The electrons and ions interact at the interface of the alloy to exchange energy.

Figure 1. AssessLIFE software: Home Page

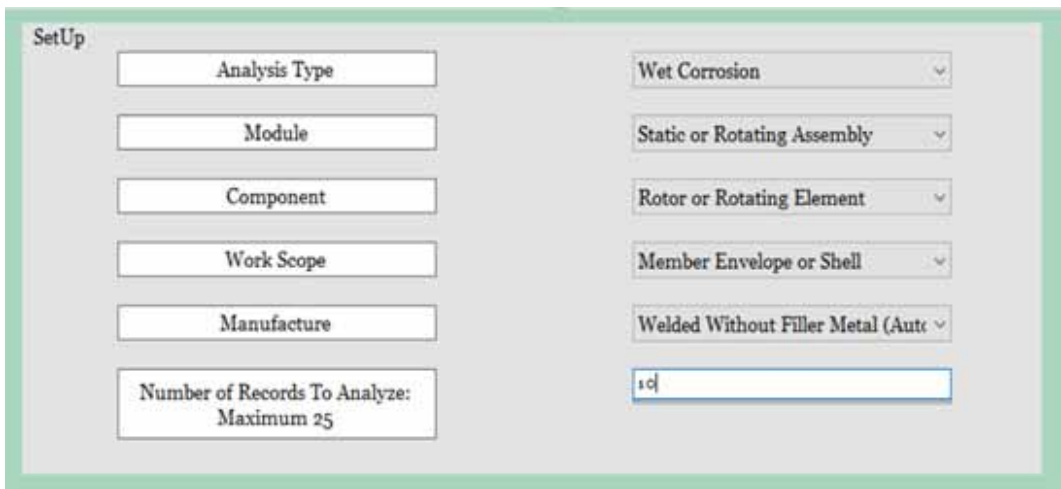


ALLOY DEGRADATION: A MULTI-DISCIPLINE CONCEPT

Corrosion is a multi-dimensional concept that requires a multi-discipline approach to fully appreciate, model, simulate, and integrate into a framework that can estimate the degradation rates of the various corrosion sub-mechanisms as well as forecast the lifespan of assets and alloys subject primarily to the corrosion degradation processes. Corrosion can be viewed from multidimensional and multidiscipline

perspectives, which include, but are not limited to, the disciplines of electronic, electrical, chemical, process, metallurgical, welding, and mechanical engineering. The corrosion degradation process overlaps with each of the specified disciplines and engages concepts and principles in these disciplines while attempting to arrive at a full and comprehensive understanding of the processes involved in the corrosion mechanism. Some of the overlap between corrosion and the specified disciplines are presented below. The AssessLIFE software models and integrates these mutual interactions within and between these specified disciplines and automates them to compute alloy or asset lifespans and analytics on degradation drivers.

Figure 2. AssessLIFE “software high-level configuration for analysis” Option



The screenshot shows a software interface titled "SetUp" with two columns of configuration options. The left column contains text input fields for "Analysis Type", "Module", "Component", "Work Scope", "Manufacture", and a box for "Number of Records To Analyze" with a sub-label "Maximum 25". The right column contains dropdown menus for "Wet Corrosion", "Static or Rotating Assembly", "Rotor or Rotating Element", "Member Envelope or Shell", and "Welded Without Filler Metal (Auto)", followed by a text input field containing the value "10".

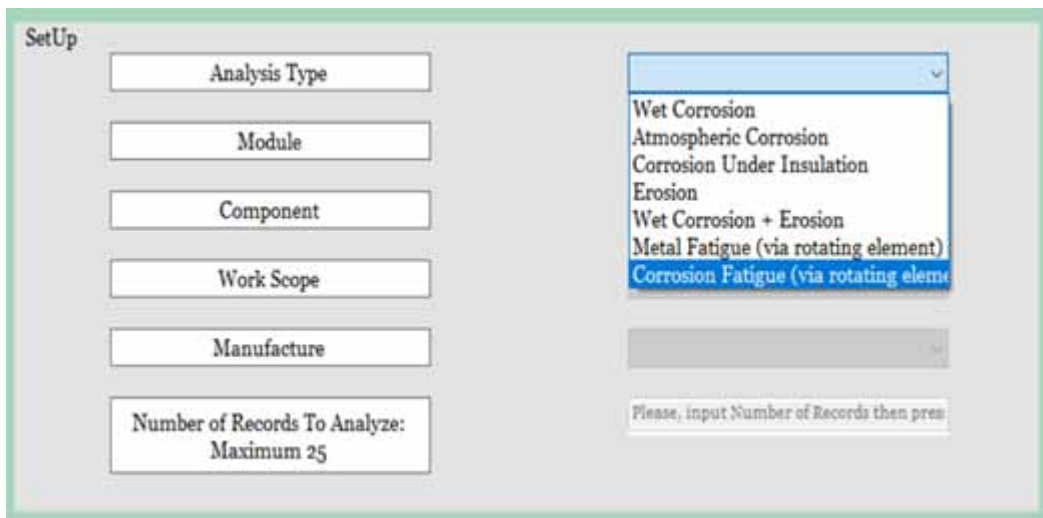
ALLOY DEGRADATION IN THE ELECTRICAL AND ELECTRONICS ENGINEERING DOMAIN

Corrosion engineering, just like electronic engineering, discusses the movement of electrons within an alloy or structure. The electrons naturally move from areas of high electron density to areas of lower electron density. However, unlike in electronic engineering where the electron flow is controlled to perform useful work, the resultant energy from corrosion processes is largely wasted. Electronics is the field of science that uses electrical principles to perform other useful work, and electricity is moving electrons. An electron is a tiny particle inside the atoms that make up everything we can feel and see, and even that which we cannot see. If we can get some electrons moving together in a wire or electrical or electronic component, we can control them to do many useful things, such as amplification (Frenzel Jr., 2018). When more electrons accumulate in a region of the alloy or structure, thereby increasing the electron density of the region, this region of higher electronic density generates a potential difference between other adjacent regions with lower electronic density. It is this potential difference or voltage that drives electron movement. In corrosion engineering, this electron movement driven by a voltage causes metal loss, while in electrical and electronic engineering, this voltage-driven electron movement is principally harnessed to perform work.

Voltage refers to an electromotive force that moves or pushes electrically charged particles like electrons, holes, negatively charged ions, or positively charged ions. Current consists of movement of electrons, ions, or simply charged particles Rauf (2014). Blume (2007) added that “Voltage is the

electric power system's potential energy source. Voltage does nothing by itself but has the potential to do work. Voltage is a push or a force. Voltage always appears between two points. Voltage always tries to push or pull current. Therefore, when a complete circuit or closed-loop path is provided, voltage will cause current to flow. The resistance in the circuit will reduce the amount of current flow and will cause heat to be provided." Hence, the corrosion process, which includes metal loss from electron movement driven by voltage, overlaps the fields of electronic and electrical engineering, where voltage drives current, which is typically harnessed to perform useful work.

Figure 3. AssessLIFE "Analysis Type" Options



ALLOY DEGRADATION IN THE CHEMICAL ENGINEERING DOMAIN

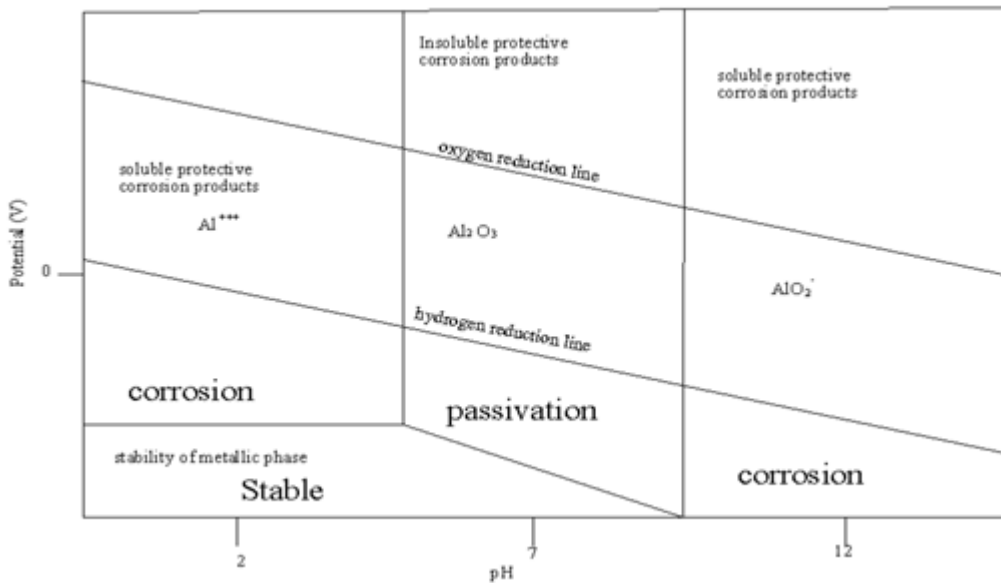
Corrosion processes overlap with the field of chemical engineering. Corrosion processes always involve chemical reactions or the exchange of chemical ions. While different electron densities form in different regions of the alloy, and electrons translate in the alloy or structure, simultaneously, chemical ions migrate about in the liquid or aqueous medium. With chemical ions, identical to electron flow processes in electrical and electronic engineering, during the corrosion processes, metal atoms at the anode electrode lose their electrons – become charged particle or ions – and enter a liquid or aqueous phase. Hence, metal ions enter into solution in a process called oxidation reactions, which occurs at the anode electrodes. The liberated electrons travel via the coupling between the anode and cathode electrodes. At the interface between the cathode and liquid, these liberated electrons reduce chemical species or ions in solution during reactions called reduction reactions. Hence, oxidation reactions occur at the anode electrode while reduction reactions occur at the cathode electrode. From the corrosion perspective, the oxidation and reduction reactions are one of the distinguishing frontiers between how corrosion processes overlap with electrical and electronic engineering and how the corrosion processes overlap with chemical engineering. Hence, unlike in the electrical and electronic domains, the chemical domain involves the oxidation and reduction of chemical species in solution.

Chemical reactions can be classified under two separate but interrelated regimes: the drive for the reaction to occur, called thermodynamics, and the rate of chemical reaction, covered by chemical kinetics. On the one hand, chemical thermodynamics can be considered analogous to voltage-

influences in electrical and electronic domains where the voltage is the driver for current to flow between regions of different voltage levels. According to Hipple (2017), “Chemical thermodynamics helps us to understand how much energy is released or consumed during a reaction, which reactions are favored, and how to enhance a reaction system to produce the most desired products and minimize raw materials and energy consumption.” For corrosion reactions specifically, Marcel Pourbaix (Pourbaix, 1974) established pH versus potential (in volts) maps of thermodynamic equilibrium diagrams called Pourbaix diagrams. The Pourbaix diagram indicates the various regions in an alloy-water system where the system experiences the drive to corrode, remain passive, or become immuned (or inert) Cicek (2013). Figure 4 shows an illustration of the Pourbaix thermodynamic corrosion diagram for aluminum.

Conversely, chemical kinetics is concerned with the rate or speed of chemical reactions – and it is analogous to electron flow domains in electrical and electronic engineering. Since corrosion reactions are chemical reactions, these corrosion reactions operate under the principles of chemical kinetics. Chemical kinetics describes how fast a reaction reaches its endpoint or equilibrium (Hipple, 2017). Figure 5 shows a representation of the corrosion kinetics diagram of pure aluminum.

Figure 4. Illustration of the Pourbaix Diagram for Aluminum (Obi, 2008)

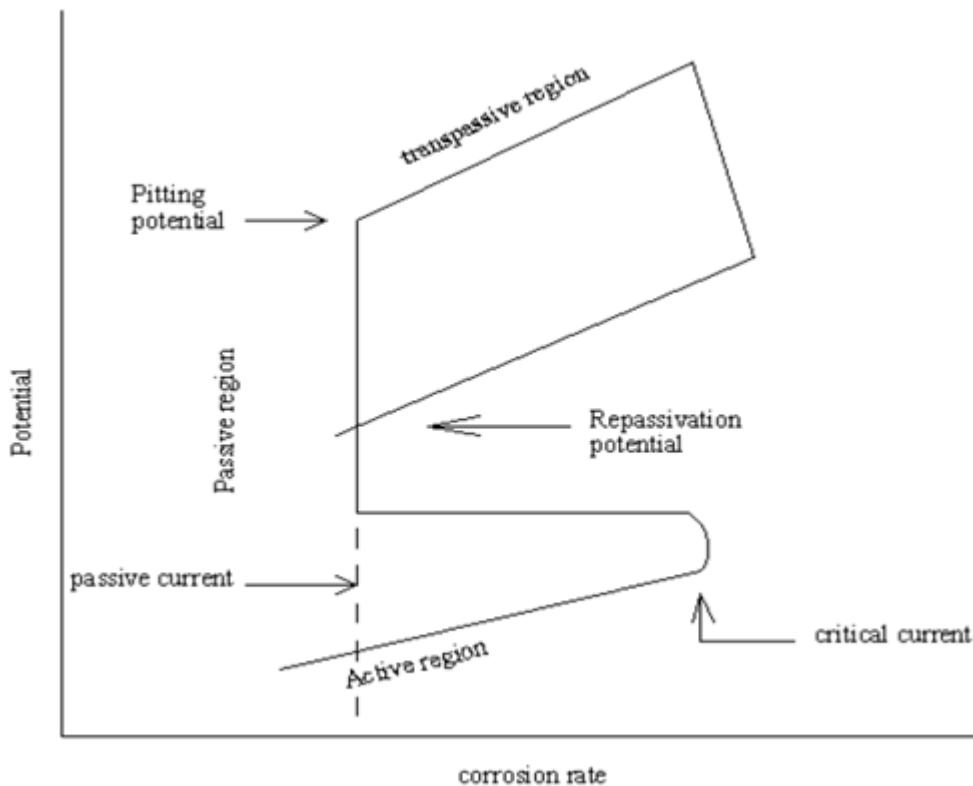


ALLOY DEGRADATION IN THE PROCESS ENGINEERING DOMAIN

Corrosion processes also interface with process engineering. Corrosion can be described as the flow of electrons in an alloy or structure resulting in metal loss as the alloy or structure interacts with its exposure environment. Hence, the variables of the exposure environment also influence corrosion processes. In industrial settings, influential environmental variables that drive corrosion are the typical process variables of plant operations. “A process is any operation or series of operations that causes physical or chemical changes in a substance or a mixture of substances” (Ghasem & Henda, 2009). The process variables include temperature, pressure, concentration, flow rates, pH, and so forth. Gladstone and Mehra (2011) described the process variable as a set of quantities that defines

the operating conditions of a chemical system. Hipple (2017) reinforced that process variables affect the outcome of chemical reactions, stating that the point of attainment of equilibrium of a chemical reaction system will be affected by temperature as well as the ratios of reactants, and for gases, the pressure as well. Sedriks (1996) discussed the different process variables that affect corrosion reactions specifically.

Figure 5. Representation of the Corrosion Kinetics Behavior of Pure Aluminum (Obi, 2008)



ALLOY DEGRADATION IN THE MECHANICAL ENGINEERING DOMAIN

The corrosion processes are mutually influenced by the decision made and actions taken in the mechanical, metallurgical, and welding domains. Mechanical, metallurgical, and welding engineering also overlap with corrosion engineering. Mechanical engineering utilizes the principles of energy, motion, and force to understand and manipulate systems. Energy, which is the capacity to do work, as well as motion and force, influence atomic and electronic behavior in an alloy or structure. Increased energy, motion, and force may cause the atoms of an alloy or structure to aggregate or to increase its electron density in certain regions or to vibrate more. The new states of the electrons may facilitate corrosion – if the electrons translate within the alloy or structure. Mechanical stress and deformation can significantly influence corrosion processes (Haanappe et al., 2001).

ALLOY DEGRADATION IN THE METALLURGICAL ENGINEERING DOMAIN

In Metallurgical engineering, it is shown that atoms and molecules (the building blocks of alloys and structures) arrange themselves in a pattern called the crystal structure (Choudary, 2003). The entities that constitute the crystal structure interact via processes such as atomic, metallic, ionic, and covalent bonding, as well as via Van Der Waals forces (Choudary, 2003). Groups of these atomic and molecular entities can aggregate to form grains whose boundaries are called grain boundaries. Grain boundaries consist of atoms in non-equilibrium positions, and as such they are high-energy regions of stability (Choudary, 2003). The structure and compositions of grains and, particularly, grain boundaries influence both the drive for corrosion to occur (corrosion thermodynamics) and the rate of corrosion processes (corrosion kinetics). In many cases, the highly alloyed, high energy, and high electron density grain boundary corrode preferentially to the grain interior (which, in comparison to the grain boundary composition, has fewer alloying elements, lower energy, and lower electron density). The difference in electron density between the grain boundary and grain (interior) can drive electrons from the boundary to the interior, resulting in the corrosion of the boundaries. This process typically results in intergranular corrosion. Figure 6 shows the grains and grain boundaries of Mg_2Si phase in aluminum alloy A535 matrix before exposure to a corroding medium of NaCl solution. Figure 7 shows the corroded Mg_2Si phase in the aluminum A535 matrix after 14 days of exposure in a neutral NaCl solution. The Mg_2Si phase had higher electron activity and density compared to the aluminum A535 matrix and thereby lost electrons to the matrix and, consequently, corroded. Figure 8 shows a higher magnification image of the corrosion damage of the aluminum A535 sample. It can be seen that at high magnification, corrosion damage preferentially selects certain locations on the surface of the sample. Typically, high-energy, high-electron density, and high-activity locations selectively undergo metal loss during corrosion activity.

ALLOY DEGRADATION IN THE WELDING ENGINEERING DOMAIN

Welding engineering describes the localized heating and rapid cooling of alloys to achieve a metallic joint (Dupont et al., 2009; Kotecki et al., 2005; Lippold, 2015; Phillips, 2016; Singh, 2012). The effects of welding include redistribution of alloying elements, addition of alloying elements via the filler-metal, creation of new grains and grain boundaries, and acceleration of grain growth in the different regions of the weld (or weldment) (Dupont et al., 2009; Ghosh, 2016; Kotecki et al., 2005; Lippold, 2015). As seen with the grain dynamics in metallurgical engineering, redistribution, creation, addition, and growth acceleration of grains and grain boundaries influence the possibility of corrosion and rates of corrosion reactions. Furthermore, welding can generate residual stresses which can induce both mechanical fractures and corrosion degradation. The different regions of a weld can have different chemical compositions, alloying elements distribution, sizes of grains, compositions of grain boundaries, and different electron densities. All these factors can induce corrosion degradation of the weldment (The Materials Information Society, 2006).

ASSESSLIFE SOFTWARE: SIMULATING ALLOY DEGRADATION VIA THE MECHANISM OF ATMOSPHERIC CORROSION

Besides “Wet Corrosion,” Figure 2 also shows that the AssessLIFE software has “Atmospheric Corrosion” and “Corrosion Under Insulation” packages with which to analyze and estimate lifespans of alloys and assets under the degradation mechanisms of atmospheric corrosion and corrosion under insulation. Atmospheric corrosion is corrosion degradation that occurs under atmospheric conditions. Like wet corrosion, atmospheric corrosion involves corrosion thermodynamics and kinetics reaction processes. However, unlike wet corrosion, which is driven by process variables (such as industrial stream temperature, pressures, concentrations, and pH), atmospheric corrosion is driven by process

variables under atmospheric conditions (such as atmospheric pressure, temperature, dewpoint, time of wetness, as well as solids, liquids, and gaseous atmospheric contaminants) (Schweitzer, 2006). Atmospheric corrosion is also location dependent. Different locations contain different degrees of atmospheric variables that influence the corrosion processes and result in different degrees of severity of corrosion damage.

Figure 6. A micrograph showing Mg_2Si grains in A535 matrix and surrounding grain boundaries before immersion in salt solution (Obi, 2008).

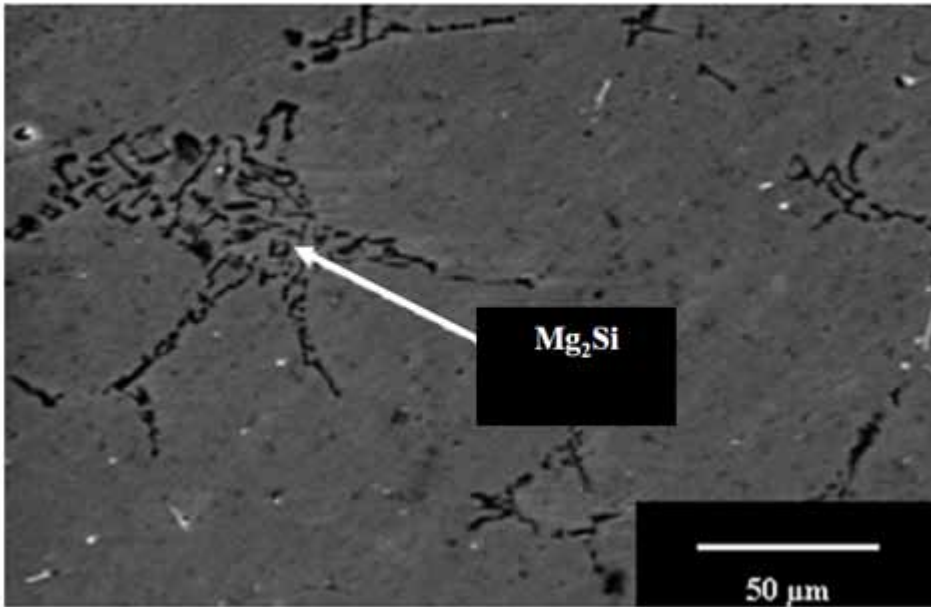


Figure 7. Optical micrograph showing the corroded surface of A535 specimen immersed in neutral salt solution for 14 days (Obi, 2008)

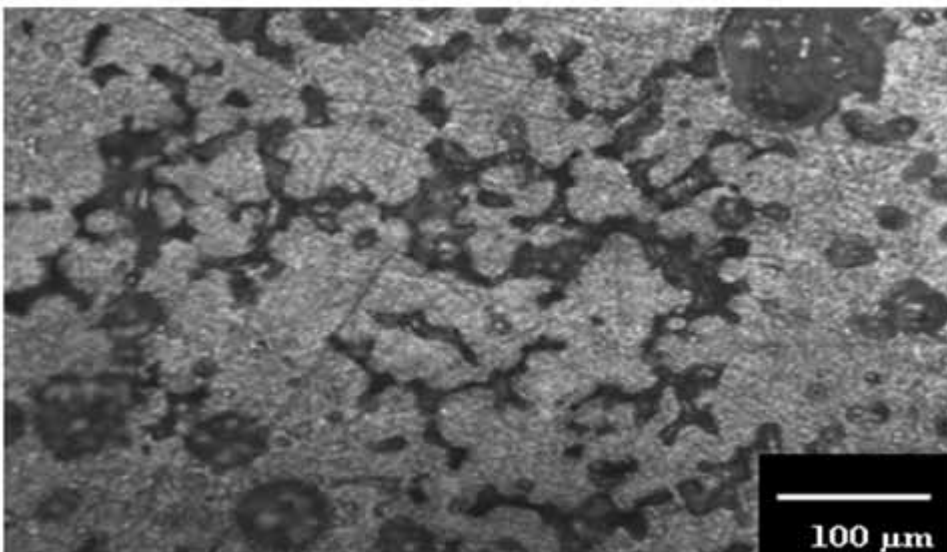
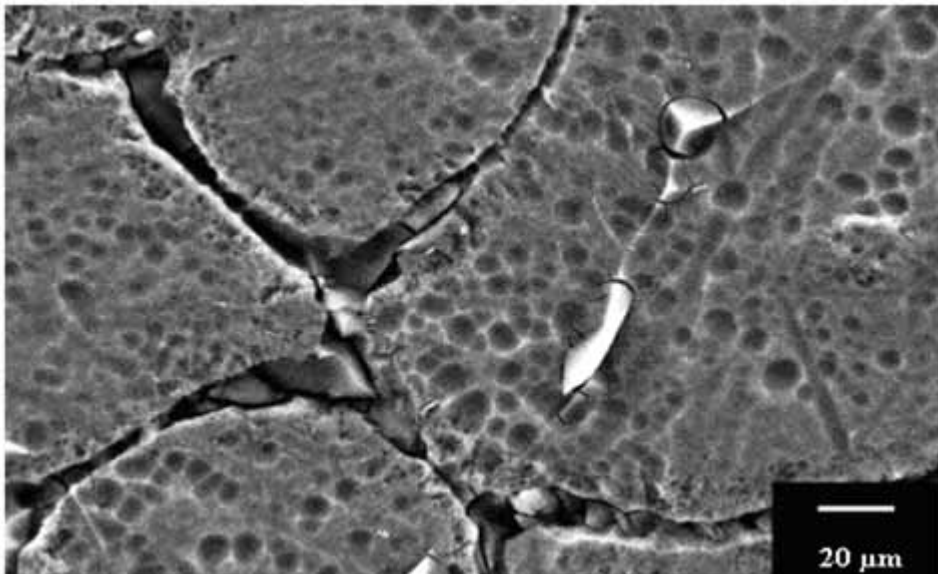


Figure 8. A micrograph of A535 alloy in neutral 3.5wt% NaCl solution for 14 days (Obi, 2008)



Because atmospheric corrosion rates are affected by local conditions, atmospheres are generally divided into the following major categories: rural, industrial, and marine. For all practical purposes, the more rural the area, with little or no heavy manufacturing operations, or with very dry climatic conditions, the less will be the problem of atmospheric corrosion. Marine environments are subject to chloride attack resulting from the deposition of fine droplets of crystals formed by evaporation of spray that has been carried by the wind from the sea (Schweitzer, 2006).

ASSESSLIFE SOFTWARE: SIMULATING ALLOY DEGRADATION VIA THE MECHANISM OF CORROSION UNDER INSULATION

Corrosion under insulation is corrosion degradation that occurs below insulation applied typically on the atmosphere-facing side of assets to prevent the ingress of moisture and other air-borne contaminants that can drive a corrosion attack of the asset. Moisture ingress via the insulation to the asset-insulation interface is a major challenge with preventing corrosion under insulation damage (Zelinka et al., 2014). At dew point temperature on exposure surfaces, liquid water condenses from water vapor in the air and wets the exposed surfaces. “The dew point is the temperature a parcel of air needs to be cooled at constant pressure for saturation (100% relative humidity) to occur” Bui et al., 2019). Similarly, some researchers defined the dew point temperature as “the temperature at which the moisture/liquid water (water vapor) in the air begins to condense,” (Ukhurebor et al., 2017). The implication of dew point temperature for corrosion under insulation becomes clear when one considers that when assets operating with high temperature streams or fluids are shut down for maintenance or production changes, the asset cools down. However, as the asset cools, it traverses the dew point temperature of surrounding air on its surfaces. At and below the dew point temperature of surrounding air, at the asset-insulation interface, water vapor within the pores of the insulation can condense and provide an environment for corrosion under insulation attack on the asset. Different types of insulation can provide different degrees of resistance to condensed water accumulation at the asset-insulation interface, and therefore, provide varying degrees of protection to the corrosion under insulation attack.

ASSESSLIFE SOFTWARE: SIMULATING ALLOY DEGRADATION VIA THE MECHANISM OF EROSION

Figure 2 also shows that the AssessLIFE software possesses “Erosion” and “Wet Corrosion + Erosion” packages. Unlike corrosion, which involves chemical reactions, erosion is the physical removal of tiny bits of the alloy by either the fluid or stream itself (fluid- or stream-induced erosion) or by the stream-borne particles (solid-particle erosion). Fluid flow is governed by two distinct regimes: the laminar-flow region and the turbulent-flow region (Taghavi-Zenouz et al., 2008). “When the flow is orderly and predictable, the flow pattern is often amenable to mathematical solutions. These flows are called laminar. In laminar flow, the individual fluid particles move along their trajectories independent of the particles in the adjacent layers” (Brown, 1991). The research also adds that the “beautiful laminar flows exist only under special conditions. If the flow conditions are altered due to increased velocity or temperature, a new flow picture may result. The mathematical solutions to the equations must also change accordingly. When there are observed waves and vortices in a flow field, the equations must yield solutions that contain these phenomena. The process of change from laminar to wavy or turbulent flow can be developed in the basic flow equations and is known as instability analysis or instability theory,” (Brown, 1991) In summary, turbulent flow is characterized by wakes, eddies, energy, and momentum transitions and losses, unpredictable fluid property changes, and a “rough” flow behavior. It is typically this “rough exchange” that detaches tiny bits of the alloy. Research has shown that turbulent flow (which initiates at a certain laminar-to-turbulent transition flow velocity) significantly increases the erosion damage on alloys or assets (Badr et al., 2005; Shehadeh et al., 2014). Shehadeh et al. (2014) found that within the chosen flow rates and contamination levels, the rates of erosion increase linearly with the increase of flow velocities. In general, the erosion rate was doubled on the transition from the laminar to the turbulent flow regime. The works of Badr et al. (2005) revealed that “the results showed a strong dependence of erosion on both particle size and flow velocity.” In addition to flow velocity, stream density also contributes to erosion damage. Stream density represents the weight (or force) of the fluid flung onto the alloy surface driven by flow velocity. Fluids with greater density are heavier than lighter fluids and tend to remove greater numbers of tiny bits of the alloy surface and, thereby, inflict more severe erosion. “Density is the sum of the mass of the molecules in a designated volume, that is, mass per unit volume. Kinetic energy is half the average molecular mass times velocity squared in this volume” (Brown, 1991). The kinetic energy and momentum (that is, mass of fluid particles multiplied by the particle velocity) of fluid particles are thereby influenced by the fluid density. “Each molecule [within the liquid] carries momentum with it in its random migration” (Brown, 1991). Both fluid kinetic energy and momentum influence energy transfer to the alloy surface and affect the severity of erosion damage inflicted on the alloy.

Erosion by stream-borne particles or solid-particle erosion occurs when solid-particles rather than the fluid itself is the principal agent of the erosion damage. A fluid or stream laden with solid particles moving at a high fluid velocity relative to the boundary of its container will impinge on the container boundary or scour the boundary of the container, thereby eroding it.

“Small solid particle impact erosion of materials occurs by the removal of material from a surface by a micromechanical deformation/fracture process. On ductile materials, the impacting particles cause severe, localized plastic strain to occur that eventually exceeds the strain to failure of the deformed material. On brittle materials, the force of the erodent particles causes cracking and chipping off micro-size pieces. These two relatively simple mechanisms are the essence of small solid particle erosion” (Levy, 1995). Parameters that influence erosion damage via solid-particle erosion include erodent density, size, hardness, shape, and impingement angle as well as target material hardness and density. “Erosion-material wastage is dependent on many interrelated factors that include the properties and structures of the target materials, the macroexposure and microexposure conditions, and the physical and chemical characteristics of the erodent particles” (Levy, 1995). AssessLIFE

software has the capability to assess the contribution of the various factors that influence both fluid-induced erosion and solid-particle erosion.

ASSESSLIFE SOFTWARE: SIMULATING ALLOY DEGRADATION VIA THE MECHANISM OF EROSION CORROSION

In addition to erosion, Figure 2 shows that the AssessLIFE software offers the “Erosion + Wet Corrosion” package for alloy degradation analysis. “Erosion + Wet Corrosion” is typically termed erosion corrosion. Erosion corrosion is the synergistic degradation resulting from the combination of wet corrosion and erosion degradation processes. “The term erosion corrosion is a combined action of mechanical abrasion and wear on the surface of metal as a consequence of fluid motion and corrosion” (Cicek, 2013). Erosion action removes the passive films on some alloys or the boundary surface of other alloys, and consequently exposes the inner vulnerable surface to the chemical reactions of corrosion attack. This iterative process repeats, and the alloy is in worse condition than if it was only under attack by either corrosion or an erosion mechanism alone.

ASSESSLIFE SOFTWARE: SIMULATING ALLOY DEGRADATION VIA THE MECHANISM OF METAL FATIGUE

Figure 2 shows that “metal fatigue (via rotating element)” and “corrosion fatigue (via rotating element)” are the last analysis packages in the current version of the AssessLIFE software. Metal fatigue is a degradation mechanism that occurs when an alloy is bent back and forth until cracks initiate after a defined number of cycles and propagate until the alloy fractures. Back and forth motions represent alternating, cyclic, fluctuating, or vacillating loadings. Back-and-forth motions are typically impacted to an alloy, component, device, or structure by alternating, vacillating, fluctuating, and cyclic forces, and stresses. “Fatigue is the progressive, localized, permanent structural change that occurs in materials subjected to fluctuating stresses and strains that may result in cracks or fracture after a sufficient number of fluctuations” (ASM International, 2020). Fatigue failure is a progressive failure driven by cyclic stress application. It is a fracture failure that occurs over time. It contrasts with the sudden stress overload failure that can occur when an inadequate cross-section is implemented on a load-carrying structural member or machine element. Like corrosion and erosion failures, metal fatigue is a time-dependent failure mechanism.

“Mechanical failure modes can be grouped into two categories: (1) instant, force, or moment dependent [or time independent], (2) time dependent. Bending, shear, torsion, and buckling happen instantly if the force/moment applied to the part is more than the design criteria. It is quite easy to calculate these failure modes since there is no uncertainty. On the other hand, erosion, corrosion, fatigue, creep, and thermal shock are time and environment dependent and cannot be controlled easily throughout the life of the part, and moreover more than one can occur at the same time causing the life of a part to decrease exponentially” (Kececi, 2019).

ASSESSLIFE SOFTWARE: SIMULATING ALLOY DEGRADATION VIA THE MECHANISM OF CORROSION FATIGUE

While metal fatigue occurs in the absence of a degrading environment or corrosive solution, corrosion fatigue is the fatigue process exposed to a corrosive medium. The synergy of corrosion and fatigue that occurs during corrosion fatigue causes failure to occur at a short number of cycles than with standard metal fatigue failure. With both metal fatigue and corrosion fatigue, “the process of failure consists of three stages: (1) Initial fatigue damage leading to crack nucleation and crack initiation, (2) progressive cyclic growth of a crack (crack propagation) until the remaining uncracked cross section

of a part becomes too weak to sustain the loads imposed, (3) final, sudden fracture of the remaining cross section” (ASM International, 2020).

ASSESSLIFE SOFTWARE: CONFIGURATION OPTIONS

The AssessLIFE software presents users with several configuration options that enable the user to define the specific details of the users’ application scenario, with the goal that the software is provided with sufficient information to model, simulate, and analyze the application scenarios. Figure 9 shows the options for the “Module” configuration selection box. The “Module” options present the different assemblies that can be analyzed by the AssessLIFE software. An assembly is a collection of parts or components joined together using various joining or coupling methods. The assemblies include rotating assembly, static assembly, piping and fittings assembly, nozzle assembly, and structural steel assembly. The “Module” configuration box defines the assembly type and feeds into the “Component” configuration selection box options that further define the type of member of the selected assembly to be analyzed. Figure 10 shows the “Component” configuration selection box options when the “Module” configuration selected option is “Rotating Assembly.”

When “Rotating Assembly” is selected in the “Module” box, only “Rotor or Rotating Element” and “Rotor Fastener” are available for analysis by the “Wet Corrosion” degradation process or mechanism. As shown in Figure 11, when “Static Assembly” is the selected option at the “Module” level, the options at the component level are “Static Asset Member” and “Cathodically Protected Asset Member.” Similarly, the selection of “Piping & Fittings” at the “Module” configuration level generates a list of piping components and fittings at the “Component” level, as Figure 12 shows. In the same vein, in Figure 13, when “Nozzle Devices” is selected at the “Module” level, a list of nozzle-related components is available as options at the “Component” configuration level. Lastly, as shown in Figure 14, selecting “structural steels” at the module level displays “structural member” as the only option available for selection at the “Component” configuration level. Hence, the AssessLIFE software enables users to mirror their real-life applications via choosing the most appropriate options in the configuration boxes, with the goal that the analysis considers the specific details of the user application scenarios.

When the “Component” configuration has been decided and selected, the “Work Scope” configuration selection box is enabled for user input. Figure 15 shows the options available to the user in the “Work Scope” selection box: “Member Envelope or Shell” and “Sleeve or Patch on Member Envelope.” The term “Member Envelope or Shell” denotes the analysis applied to the original envelope or boundary of the asset member specified, while “Sleeve or Patch on Member Envelope” denotes the analysis applied to a repair sleeve or patch on the member’s original boundary or envelope. Figure 16 shows that below the “Work Scope” configuration level in the AssessLIFE software is the “Manufacture” configuration. The “Manufacture” configuration box enables the user to specify the method of manufacture of the selected member to be analyzed. The method of manufacture of a part or component can often influence the type or speed of degradation that the member experiences in service. The “Manufacture” dropdown list includes “Welded Without Filler Metal (Autogenous),” “Welded with Filler Metal,” “Fastened,” and “Cast.”

The last user configuration box in the “Setup” domain enables users to enter the number of records of asset members that the user wishes to analyze. The “Number of Records to Analyze: Maximum 25” data entry box ensures that all the software pages downstream of the HomePage contain the required number of records for all the input fields required by the AssessLIFE software to estimate lifespans and trajectories of degradation drivers.

Figure 9. AssessLIFE “Module” Options

The screenshot shows the 'Setup' window of the AssessLIFE software. On the left side, there are six input fields: 'Analysis Type', 'Module', 'Component', 'Work Scope', 'Manufacture', and 'Number of Records To Analyze: Maximum 25'. On the right side, there are three dropdown menus. The top dropdown is set to 'Wet Corrosion'. The middle dropdown is open, showing a list of options: 'Rotating Assembly' (highlighted in blue), 'Rotating Assembly', 'Static Assembly', 'Piping & Fittings', 'Nozzle Devices', and 'Structural Steels'. The bottom dropdown is currently empty. Below the dropdowns, there is a text prompt: 'Please, input Number of Records then pres'.

Figure 10. AssessLIFE “Component” Options when “Module” option “Rotating Assembly” is selected

The screenshot shows the 'Setup' window of the AssessLIFE software with the 'Module' dropdown set to 'Rotating Assembly'. The 'Component' dropdown is open, showing a list of options: 'Rotor or Rotating Element' (highlighted in blue) and 'Rotor Fastener'. The other fields and dropdowns are the same as in Figure 9. The text prompt at the bottom is: 'Please, input Number of Records then pres'.

Figure 11. AssessLIFE “Component” Options when “Module” option “Static Assembly” is selected

The screenshot shows the 'Setup' window of the AssessLIFE software. On the left, there are several input fields: 'Analysis Type', 'Module', 'Component', 'Work Scope', 'Manufacture', and 'Number of Records To Analyze: Maximum 25'. On the right, there are dropdown menus for 'Wet Corrosion' (set to 'Wet Corrosion'), 'Module' (set to 'Static Assembly'), and 'Component'. The 'Component' dropdown is open, showing two options: 'Static Asset Member' (highlighted in blue) and 'Cathodically Protected Asset Member'. Below the dropdowns, there is a text box with the prompt 'Please, input Number of Records then pres'.

Figure 12. AssessLIFE “Component” Options when “Module” option “Piping & Fittings” is selected

The screenshot shows the 'Setup' window of the AssessLIFE software. On the left, there are several input fields: 'Analysis Type', 'Module', 'Component', 'Work Scope', 'Manufacture', and 'Number of Records To Analyze: Maximum 25'. On the right, there are dropdown menus for 'Wet Corrosion' (set to 'Wet Corrosion'), 'Module' (set to 'Piping & Fittings'), and 'Component'. The 'Component' dropdown is open, showing a list of options: 'Straight Section', 'Regular Screwed 90deg Elbow', 'Long Radius Screwed 90deg Elbow', 'Regular Flanged 90deg Elbow', 'Regular Screwed 45deg Elbow', 'Long Radius Flanged 45deg Elbow', 'Screwed Return 180deg Bend', 'Regular Flanged Return 180deg Bend', 'Long Radius Flanged Return 180deg Bend', and 'Screwed Tee Line Flow'. The list is scrollable, with a scrollbar on the right side.

Figure 13. AssessLIFE “Component” Options when “Module” option “Nozzle Devices” is selected

The screenshot shows the 'Setup' window of the AssessLIFE software. On the left, there are several input fields: 'Analysis Type', 'Module', 'Component', 'Work Scope', 'Manufacture', and 'Number of Records To Analyze: Maximum 25'. On the right, there are dropdown menus for 'Wet Corrosion' (set to 'Wet Corrosion'), 'Module' (set to 'Nozzle Devices'), and 'Component'. The 'Component' dropdown is open, showing a list of options: 'Reducer', 'Expander', 'Expander (Tapered / Chamfered)', 'Outlet Nozzle (Tapered / Chamfered)', 'Outlet Nozzle (Inward projecting pip', 'Outlet Flow (No Nozzle)', and 'Outlet Nozzle (Rounded edge)'. The list is scrollable, with a scrollbar on the right side.

Figure 14. AssessLIFE “Component” Options when “Module” option “Structural Steels” is selected

The screenshot shows the 'Setup' window of the AssessLIFE software. On the left side, there are several input fields: 'Analysis Type', 'Module', 'Component', 'Work Scope', 'Manufacture', and 'Number of Records To Analyze: Maximum 25'. On the right side, there are four dropdown menus. The first dropdown is set to 'Wet Corrosion', the second to 'Structural Steels', and the third to 'Structural Member'. The fourth dropdown is currently empty. Below the dropdowns, there is a text prompt: 'Please, input Number of Records then pres'.

Figure 15. AssessLIFE “Work Scope” Options

The screenshot shows the 'Setup' window of the AssessLIFE software. On the left side, there are several input fields: 'Analysis Type', 'Module', 'Component', 'Work Scope', 'Manufacture', and 'Number of Records To Analyze: Maximum 25'. On the right side, there are four dropdown menus. The first dropdown is set to 'Wet Corrosion', the second to 'Structural Steels', and the third to 'Structural Member'. The fourth dropdown is open, showing two options: 'Member Envelope or Shell' and 'Sleeve or Patch on Member Envelope'. Below the dropdowns, there is a text prompt: 'Please, input Number of Records then pres'.

Figure 16. AssessLIFE “Manufacture” Options

The screenshot shows the 'Setup' window of the AssessLIFE software. On the left side, there are several input fields: 'Analysis Type', 'Module', 'Component', 'Work Scope', 'Manufacture', and 'Number of Records To Analyze: Maximum 25'. On the right side, there are four dropdown menus. The first dropdown is set to 'Wet Corrosion', the second to 'Static or Rotating Assembly', the third to 'Rotor or Rotating Element', and the fourth to 'Member Envelope or Shell'. The fourth dropdown is open, showing four options: 'Welded Without Filler Metal (Autogenous)', 'Welded With Filler Metal', 'Fastened', and 'Cast'. Below the dropdowns, there is a text prompt: 'Please, input Number of Records then pres'.

ASSET MEMBER LIFESPAN ESTIMATION: THEORETICAL BACKGROUND

Each degradation mechanism amongst corrosion, erosion, and fatigue has different sets of mathematical models that an analyst may employ to estimate its degradation rate and, thereafter, the lifespan of the member subjected to that degradation mechanism. In their works, many researchers have either stated mathematic models for asset lifespan estimation (ASM International, 2020; Ebeling, 1997; Elfergani et al., 2017; Jones, 1996; Kececi, 2019; Levy, 1995; Obi, 2008; Okonkwo, 2014) or have advanced numerous mathematical formulas with which lifespan of asset members subjected to the specified degradation mechanism can be computed (Casesnoves et al., 2017; Kosa et al., 2017; Levy et al., 1983; Stack et al., 1995). The primary purpose of the AssessLIFE software is to estimate the life of a machine or structural member, given the use conditions of the part or member.

According to Kececi (2019), it is quite easy to calculate the lifespan of time independent failure modes since there is no uncertainty. For time-dependent failures, it is possible to find the life of a part with experimentation. Also, depending on the working conditions of the part, the time-dependent mechanical failure mechanisms should be calculated, and the life of the part should be known.

AssessLIFE software does not attempt to estimate lifespan for time-independent failure mechanisms. For example, the AssessLIFE software does not estimate the lifespan of a member if a cross-section does not contain sufficient material to withstand all forces, stresses, and loadings that the part will be subjected to. Specifically, the AssessLIFE software does not compute lifespan for stress-overload failures from bending, shear, torsion, and buckling. However, for the major time-dependent failure modes, the current version of the AssessLIFE software has the capability to estimate lifespans for the specified time-dependent failure modes, namely, corrosion, erosion, metal fatigue, and corrosion fatigue.

The beneficiaries of asset lifespan generated by the AssessLIFE software include, but are not limited to:

- Managers (who oversee asset-related budgets)
- Legal teams (who adjudicate over asset-related disputes)
- Insurance teams (who assess risks for insurance coverage)
- Engineers (who implement capital budgets as well as assess assets for safety and productivity)
- Fabricators (who implement engineering designs)
- Inspectors (who assess and report on asset status)

The pain points that the AssessLIFE software addresses with solutions include, but are not limited to:

- Asset safety and health assessment (the AssessLIFE software assesses physical asset degradation over time and generates status reports)
- Production loss (the AssessLIFE software ensures that assets are built from the most appropriate alloys and welds. Appropriate selection of alloys and welds facilitates continuous production)
- Maintenance cost overruns (the AssessLIFE software generates asset inspection time frames ahead of possible time-dependent failures that facilitate pro-active remedial actions)
- Legal assessment (the AssessLIFE software computes asset lifespan based on the alloy of construction and ambient exposure environments, which inform legal teams if the appropriate early-phase decisions were made)
- Insurability assessments (the AssessLIFE software computes lifespans and the remaining life of metallic physical assets, which enables insurers quantify asset insurability)
- Engineering decision-making (the AssessLIFE software computes and generates rates of degradation drivers and lifespans to ensure that the most appropriate engineering decisions are made)

- Fabrication decision-making (the AssessLIFE software proposes to fabricators information on the most appropriate welds for the exposure environment)
- Inspection preparation (the AssessLIFE software provides inspectors with possible degrading mechanisms and expected physical damage features so that the most appropriate inspection tools and techniques can be selected)

In summary, the AssessLIFE software is a solution platform that analyzes and reveals (at design time or at operating time) if the industrial physical asset made of metals, alloys, and welds can survive their exposure or ambient conditions. The software also reveals when time-dependent premature failure is likely to occur. The AssessLIFE software aims to provide asset information for better financial and technical decision-making by managers, engineers, legal teams, insurance teams, fabricators, and inspectors. Furthermore, the AssessLIFE software can generate great financial and safety benefits for all stakeholders.

Asset degradation lifespans can only be treated under a specified degradation mechanism such as corrosion, erosion, or fatigue. Each of these degradation mechanisms is unique and proceeds according to its own processes that eventually culminate in the failure of the part, member, or assembly. Corrosion, erosion, or fatigue is influenced by unique sets of inputs (emanating from either or a combination of the design engineer, operator, field conditions, or environmental conditions), and each of the mechanisms is driven to failure by unique sets of intermediate variables.

MODELING LIFESPAN UNDER CORROSION DEGRADATION MECHANISM

To model the lifespan of an asset member subjected to corrosion degradation, it is imperative to analyze the corrosion processes defined by the specific sub-mechanism that drives the corrosion damage. The sub-mechanisms of corrosion damage include, but are not limited to (Cicek, 2013):

1. General corrosion (typified by broad metal loss on the surface of the asset or alloy)
2. Pitting corrosion (depicted by perforation of the asset or alloy)
3. Crevice corrosion (depicted by localized aggressive attack on metals in close contact with corrosive stagnant fluid trapped between them)
4. Galvanic corrosion (exemplified by loss within two dissimilar regions of a structure of which metal loss occurs on one region of structure [the anode or active region], which is in electrical or physical contact with the protected region of the structure [the cathode or passive region])
5. Stress corrosion cracking (typified by cracks initiated by a combined action of stress and corrosion)
6. Intergranular corrosion (characterized by corrosion of grain boundaries leading to a compromised grain structure)
7. Erosion corrosion (depicted as metal loss in areas of high fluid velocity or solid-particle action)
8. Caustic embrittlement (characterized by cracks initiated by very high pH)
9. Hydrogen embrittlement (exemplified by cracks and fracture initiated by gas pressure when atomic hydrogen infiltrates into the metal crystal combines to form vastly higher-volume molecular hydrogen)
10. Stray-current corrosion (depicted by metal loss that occurs when current flows between unprotected assets and cathodically protected assets)
11. Microbial or biocorrosion (corrosion damage that is caused by microbes and other living organisms)
12. Corrosion fatigue (typified by damage resulting from the combined action of corrosion and fatigue, resulting in accelerated failure rate)

Several researchers (Jones, 1996; Obi, 2008) showed that the rate of degradation propagated by general corrosion can be modeled by

$$CR \left(\frac{mm}{yr} \right) = \frac{87.6W}{DA t} \quad (1)$$

where 87.6 is a constant, W is weight loss in mg, D is density in g/cm^3 , A is surface area in cm^2 , and t is time in hours.

Consequently, the lifespan of the member with thickness, $T(mm)$ is

$$Lifespan(yr) = \frac{T(mm)}{CR \left(\frac{mm}{yr} \right)} \quad (2)$$

Subir (2010) proposed an alternative method to estimate the corrosion rate of mild steel in water using interpolation, regression, and factorial design. Furthermore, Soares et al. (2011) modeled the individual effects of the different environmental or ambient parameters that drive the uniform corrosion rate of carbon steel alloy. The efforts of these research works show that there are various pathways by which the degradation process can be quantified. The goal is always to represent complex natural and physical processes using representative mathematical models that deliver outcomes that mimic reality as closely as possible. Figure 17 shows a laboratory setup with which Obi (2008) modeled the general corrosion rate of alloys.

Beside general corrosion, to model pitting corrosion, the American Society for Testing and Materials (ASTM International, 2003) provided the following insights on a key parameter, the critical pitting temperature (CPT), that governs the initiation and propagation of pits on an alloy. The critical pitting temperature is an experimentally and statistically determined temperature above which pits initiate on an alloy. The CPT of an alloy is modeled by:

$$CPT(^{\circ}C) = (2.5 \times \%Cr) + (7.6 \times \%Mo) + (31.9 \times \%N) - 41.0 \quad (3)$$

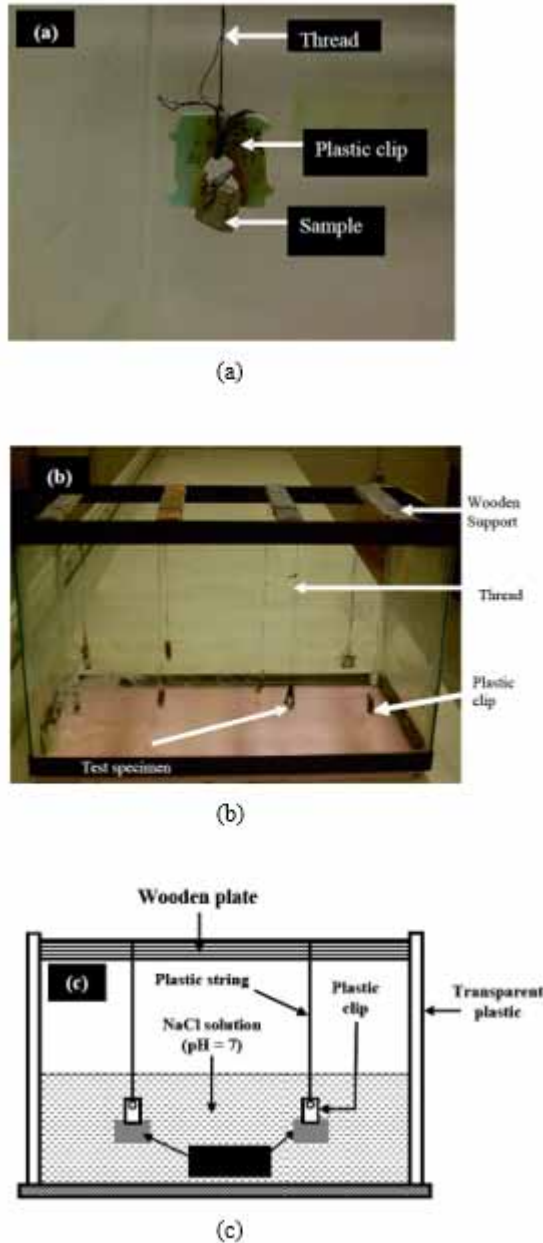
where %Cr is weight percent content of chromium in the alloy, %Mo is the weight percent content of molybdenum in the alloy, and %N is the weight percent content of nitrogen in the alloy. Hence, in the presence of chlorides (or other corrodents), when the exposure, ambient, or operating temperature is greater than the CPT, the alloy is susceptible to pitting corrosion attack. Additional computations can be performed with the CPT parameter to arrive at the lifespan of the alloy subjected to pitting corrosion attack.

Similar to pitting corrosion, the ASTM also provided insights into modeling crevice corrosion. Crevice corrosion can be modeled via the determination of the critical crevice temperature (CCT). The CCT is an experimentally and statistically determined temperature above which crevice corrosion attack on an alloy initiates and progresses. Hence, in the presence of chlorides (or other corrodents), when the exposure, ambient, or operating temperature is greater than the CCT, the alloy is susceptible to crevice corrosion attack – if a stagnant fluid is trapped between two adjacent narrowly separated surfaces of which one is a susceptible metal or alloy. Additional computations can be performed with the CCT to arrive at the lifespan of the alloy subjected to crevice corrosion attack. The CCT of an alloy is modeled by

$$CCT(^{\circ}C) = (3.2 \times \%Cr) + (7.6 \times \%Mo) + (10.5 \times \%N) - 81 \quad (4)$$

where %Cr is weight percent content of chromium in the alloy, %Mo is the weight percent content of molybdenum in the alloy, and %N is the weight percent content of nitrogen in the alloy. Figure 18, Figure 19, Figure 20, Figure 21, and Figure 22 show laboratory devices with which Obi (2008) determined the CPT and CCT, respectively, of alloys.

Figure 17. Weight-loss corrosion test apparatus: (a) specimen suspended by plastic clip and thread (b) immersion corrosion cell (c) a schematic of the immersion corrosion cell (Obi, 2008)



Welds are also subjected to similar conditions as alloys and can also suffer general, pitting, and crevice corrosion attack (Dupont et al., 2009; Kotecki et al., 2005; Lippold, 2015; Phillips, 2016). The metallurgy of welds is more complex than that of alloys since welds are typically air-cooled to room temperature at cooling rates much faster than those of alloys. Alloys are typically control-cooled in furnaces to room temperature. The rapid cooling rates of welds can create intermediate phases – and even deleterious phases – that can actively facilitate different types of corrosion attack. Furthermore, the physical, mechanical, and chemical integrity of welds are influenced by additional factors such as weld current and voltage, travel speed, welding gases, contamination of weld surfaces, and weld defects. These factors can further complicate the susceptibility of welds to corrosion attack and the assessment of welds for adequacy and integrity. The AssessLIFE software estimates the corrosion lifespan of welds using a varying modification of Equations (1), (2), (3), and (4).

Figure 18. The ECM8 electrochemical multiplexer system equipped with a PCI4 potentiostat (Obi, 2008)



MODELING LIFESPAN UNDER EROSION DEGRADATION MECHANISM

Erosion can be described as the continuous removal of tiny pieces of the target alloy by either a rapidly flowing turbulent fluid or by solid particles transported by the fluid. Many researchers (Casesnoves et al., 2017; Kosa et al., 2017; Levy, 1995; Levy et al., 1983, Okonkwo, 2014; Stack et al., 1995) modeled and advanced mathematical formulation of the degradation caused by erosion. A model of the erosion attack on alloys was postulated via the works of Okonkwo (2014) and Wada et al. (1987) as

$$E \propto \left(\frac{H_t}{H_p}\right)^w \quad (5)$$

where E is the erosion rate, H_t is the target material hardness, H_p is the eroding particle material hardness, and w is an empirically determined exponent. The model accounted for the importance of

alloy hardness of both the target material and the stream-borne solid particles. However, it failed to account for the importance of stream velocity. Hutchings' (1992) mathematical model included the effect of stream velocity and target material density,

Figure 19. Magnified view of the working electrode holder (Obi, 2008)

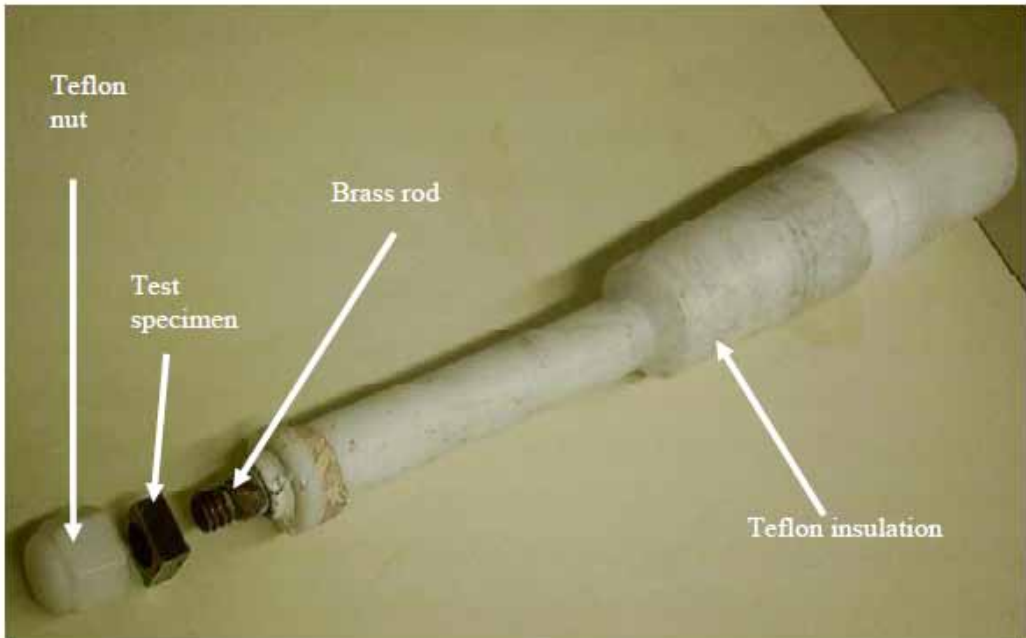


Figure 20. Working electrode, reference electrode (SCE) and graphite counter electrode used in the study (Obi, 2008)

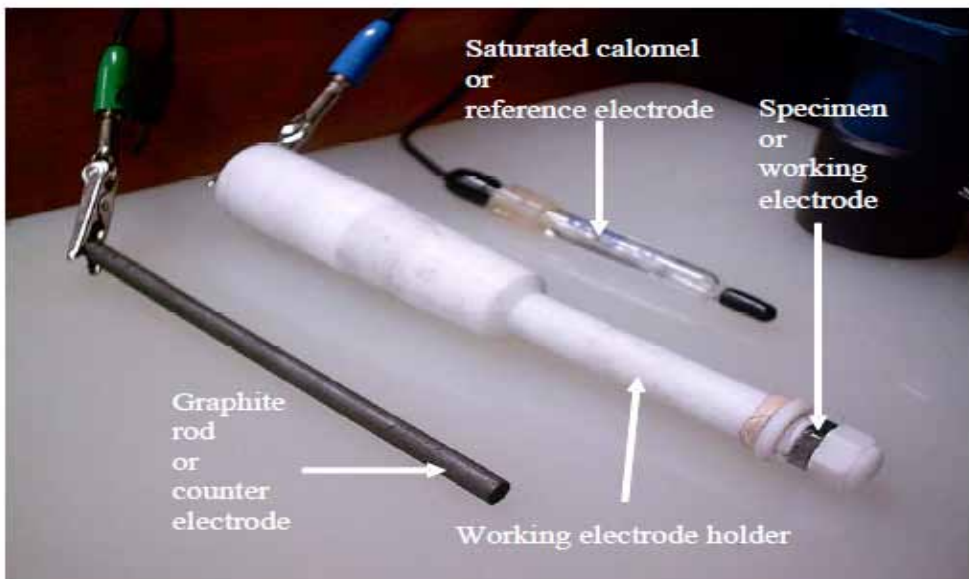


Figure 21. A schematic diagram of the working electrode and holder assembly (Obi, 2008)

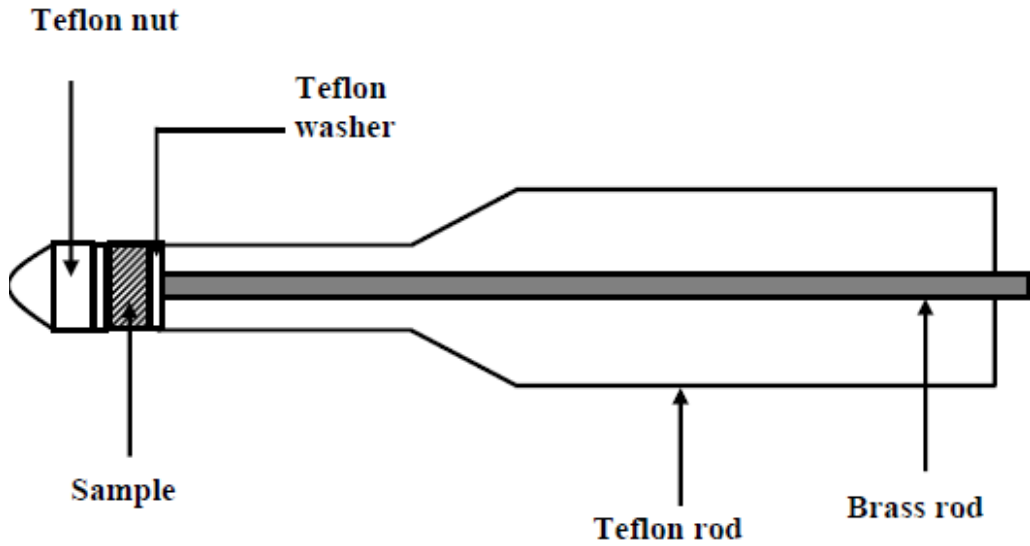
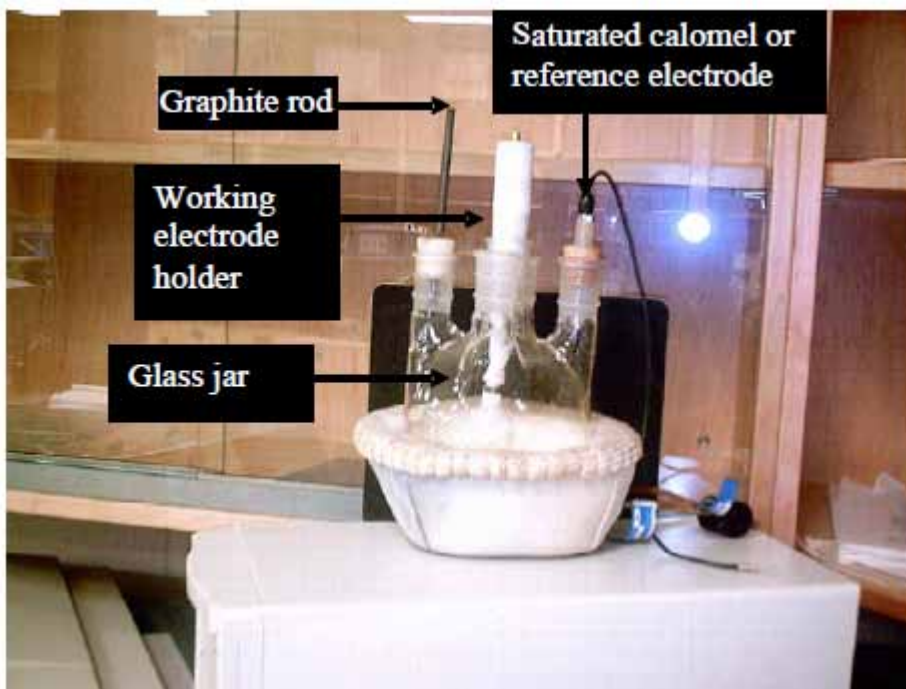


Figure 22. Corrosion cell and electrodes used in electrochemical measurements (Obi, 2008)



$$E = \frac{kp v^2}{2H} \quad (6)$$

where E is the mass of material eroded, v is the mean solid-particle velocity, H is the hardness of the erodents, p is the density of target material, and k is the wear coefficient. Hutchings (1992) had earlier formulated Equation (6) to include the impact angle of the stream solid-particles represented as alpha,

$$E = \frac{kp(v \sin \alpha)^{2.5}}{H(s)} \quad (7)$$

The study presented by Levy (1995) showed numerous mathematic models that apply to erosion damage and cover the influences of particle shape, attack angle, particle strength and density, and particle velocity, as well as target material hardness and density. The relevant mathematical models can be employed to compute the erosion rates on alloys. With the erosion rates computed, the lifespan of an alloy of thickness, $T(mm)$ under a primarily erosion attack can be estimated by the model

$$Lifespan(yr) = \frac{T(mm)}{E\left(\frac{mm}{yr}\right)} \quad (8)$$

MODELING LIFESPAN UNDER FATIGUE DEGRADATION MECHANISM

Fatigue is the failure mode that can occur when an alloy or an asset member is subjected to fluctuating or alternating stresses, forces, or loadings, which drive the alloy or asset member to initiate and propagate cracks that result in fracture of alloy or asset member. Fatigue can weaken an alloy or asset member when the member is subjected to back-and-forth loading. Stress concentration created by notches, tight radii, rough surface profile, defects in the alloy or asset member, and other features that raise stress levels (or stress concentration drivers) in the member can accelerate fatigue failure. The number of cycles to failure or lifespan of an alloy or asset member, especially when stress concentration drivers are present, can be modeled by the strain life equation (ASM International, 2020; Kececi, 2019),

$$\frac{\Delta \varepsilon}{2} = \frac{\Delta \varepsilon_e}{2} + \frac{\Delta \varepsilon_p}{2} \quad (9)$$

where $\Delta \varepsilon_e$ is the elastic strain amplitude and $\Delta \varepsilon_p$ is the plastic strain amplitude.

According to the Coffin-Manson formula presented in the works of ASM International (2020) and Kececi (2019),

$$\frac{\Delta \varepsilon_p}{2} = \varepsilon_f (2N_f)^c \quad (10)$$

where ε_p is the plastic strain amplitude, ε_f is the fatigue ductility coefficient, N_f is the number of cycles before failure, and c is the Cofflin's exponent.

Furthermore, as presented in the same works, the number of cycles to failure or lifespan can be extended by applying the Basquin formula

$$\frac{\Delta\varepsilon_e}{2} \sim \frac{\Delta\sigma}{2} = \sigma_f (2N_f)^b \quad (11)$$

where $\frac{\Delta\sigma}{2}$ is the stress amplitude, N_f is the number of cycles before failure, b is the Basquin's exponent, and σ_f is the fatigue strength coefficient.

for one-dimensional loading,

$$\frac{\Delta\varepsilon_e}{2} = \frac{\Delta\sigma}{2E} = \frac{\sigma_a}{E} \quad (12)$$

where E is Young's Modulus, σ_a is stress amplitude, and $\Delta\sigma$ is the stress range. substituting equations (9), (10), and (11) into equation (12),

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma_f}{E} (2N_f)^b + \varepsilon_f (2N_f)^c \quad (13)$$

The number of cycles to failure or the lifespan of an alloy or asset member subjected to fatigue load can be estimated as

$$2N_f = \left(\frac{\varepsilon_f E}{\sigma_f} \right)^{\frac{1}{(b-c)}} \quad (14)$$

Based on fatigue loading of an asset member, the AssessLIFE software models and estimates the lifespan of asset members subjected to the fatigue degradation process. Since welds and discontinuities (that is, areas of high stress concentration resulting from typically notches, tight-radii, weld caps, and weld defects, etc.) are particularly vulnerable to the initiation events of fatigue failure, the AssessLIFE software can discriminate between the fatigue vulnerabilities of different types of welds and different discontinuity features employed during the manufacture of asset members into machine or structural assemblies. In addition to fatigue analysis of plain members with the aim to estimate the lifespan of the member, the AssessLIFE software also analyzes the contribution of the different weld types and discontinuity features to both the possibility of occurrence of fatigue failure and to lifespan of the considered asset member.

MODELING CUMULATIVE DAMAGE AND REMAINING LIFESPAN OF AN ALLOY OR ASSET MEMBER

Some researchers (Ebeling, 1997; Ertas, 2012) have documented mathematical models that track the progress of cumulative damage on structures. As presented by Ebeling (1997), "if the damage

rate depends only on the amount of damage and not on any past history,” the progressive cumulative damage severity can be generalized by Miner’s rule,

$$\sum_{i=1}^n \frac{t_i}{L_i} = 1 \quad (15)$$

where t_i = the amount of time at stress or damage level i , and L_i is the expected lifetime at stress or damage level i .

Using Miner’s rule, the remaining lifespan of an asset can be estimated when two or more stress or damage levels are considered via the model

$$\frac{t_1}{L_1} + \frac{t_2}{L_2} = 1 \quad (16)$$

where t_1 and t_2 = the amount of time at stress or damage level 1 and 2, respectively, and L_1 & L_2 is the expected lifetime at stress or damage level 1 and 2, respectively.

On further simplification,

$$t_2 = L_2 - \frac{L_2}{L_1} t_1 \quad (17)$$

If the lifespan at damage level 1 (L_1) is known and the exposure times of the asset at damage level 1 and 2 (t_1 and t_2) are known, the remaining life L_2 of asset member or alloy subjected to cumulative damage is estimated by

$$L_2 = \frac{L_1 t_2}{L_1 - t_1} \quad (18)$$

Using similar mathematic models, the AssessLIFE software has the capability to estimate the remaining life of an alloy or asset member. The remaining life computation is a particularly beneficial service provided by the AssessLIFE software. The capability to compute the remaining lifespan of asset members or alloys is coupled to the software’s capability to determine the lifespan of members under different degradation mechanisms such as corrosion, erosion, and fatigue. Further to the determination of lifespan of an alloy or asset member under different degradation mechanisms and exposure conditions, the software can thereafter apply these lifespans in the remaining life models (Equations [15], [16], [17], and [18]) to progressively cumulative damage done by the antecedent damage mechanism and estimate the remaining lifespan of the exposed asset member or alloy.

OVERVIEW OF THE ASSESSLIFE SOFTWARE

The AssessLIFE software models, integrates, and automates the degradation processes of alloys in asset members to generate asset lifespan analytics. The AssessLIFE software models many practical alloy and weld selection decision-making tasks. Modeling attempts to transfer physical asset attributes

and user data into mathematic attributes that can be manipulated, transformed, x-rayed, diagnosed, assessed, dissected, and synthesized using the myriad mathematical principles, theorems, theories, concepts, and formulations that have been collated since the dawn of science and technology.

The AssessLIFE software integrates the concepts in and from many engineering fields and employs each field's specific mathematical models to analyze the degradation processes within the domain of the specific engineering field. The engineering disciplines include mechanical, electrical, electronic, metallurgical, materials, process, chemical, welding, and corrosion engineering. Integrating involves synthesizing related or connected engineering principles, theorems, theories, concepts, and formulations from the different engineering disciplines with which to solve multi-disciplinary engineering problems and provide multi-discipline engineering solutions.

The AssessLIFE software performs automation of degradation to estimate asset lifespan and degradation drivers by using tested and proven scientific analytical computations, forecasting, prediction, and analytics. By automating the process of degradation using mathematical models, and subsequently, estimating the asset-member lifespans as well as other vital degradation statistics, the AssessLIFE software can assess the health status of assets and their members exposed to intended service conditions or exposed to unexpected or rare upset conditions.

An asset is pictured, depicted, or represented as an entity that is built up from multiple assemblies – either from welded assemblies (or weldment) or from fastened assemblies – as shown in Figure 23 and Figure 24. The AssessLIFE software contains more than 60 different assembly scenarios.

The butt-welded assembly (Figure 23) and/or the fillet-welded assembly (Figure 24) can be interlaced multiple times to constitute industrial physical assets such as tanks, pipings, evaporators, crystallizers, pressure vessels, compactors, screens, condensers, boilers, and so on. An asset may be composed of one identical assembly or many dissimilar assemblies. Each assembly can be analyzed by the AssessLIFE software to estimate its lifespan and other vital health statistics. As shown in Figure 23 and Figure 24, with the AssessLIFE software, different alloys can be assigned to “Alloy 1” and “Alloy 2.” Thereafter, the software user can input service conditions. Using the user input data, the AssessLIFE software estimates the lifespan of the alloy and its other vital health statistics. Similarly, different weld filler metals can be assigned to “Filler-Metal Weld” along with input service conditions. With these user inputs, the AssessLIFE software can also estimate the lifespan of the different regions of the weld. Consequently, the AssessLIFE software can determine the lifespan of a user-defined weldment.

Figure 23.A butt weld assembly

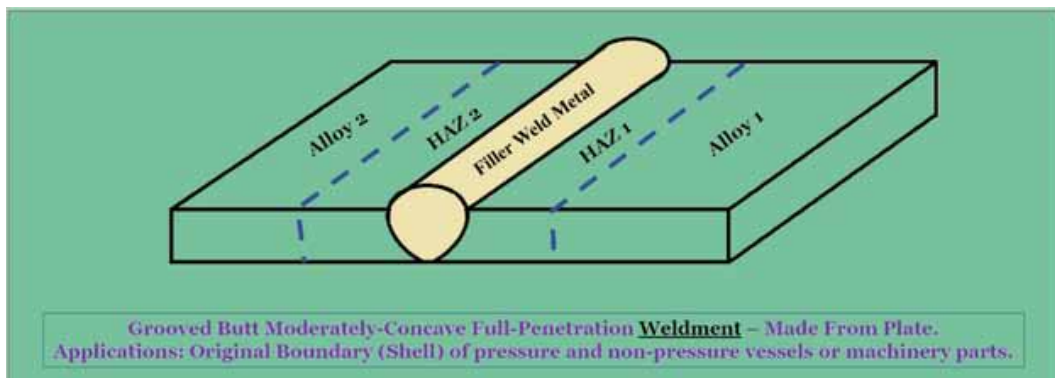
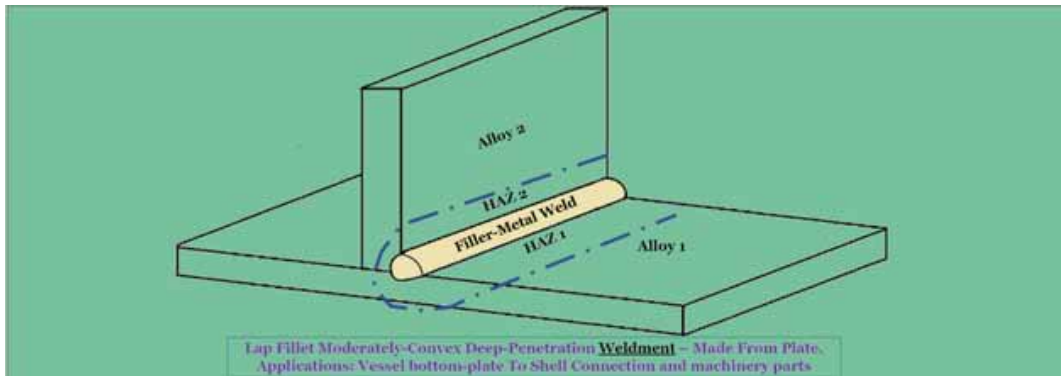


Figure 24. A fillet weld assembly



For analysis via the “wet corrosion” degradation mechanism, the AssessLIFE software commences with an information window called “InfoPage,” as shown in Figure 25. The “InfoPage” defines all relevant terms employed in the software. This window also displays the pictures of the assembly configuration selected for analysis. The goal of the “InfoPage” is to enhance the user-friendliness of the software. For the “wet corrosion” analysis type, the next window of the software, the “Asset ID” (Figure 26), contains asset identification information. This page enables the user to input identification information for each asset to be analyzed. Subsequently, the user selects alloys and welds in the “Alloy and Welds Select” window (Figure 27). The alloy configuration box is a dropdown box that lists more than 400 different alloys that are selectable from AssessLIFE version 1.0. Future versions of the AssessLIFE software will add many more alloys to the current list of alloys. Similarly, the weld filler metal configuration box is a dropdown list with more than 350 different weld filler metals that can be selected from AssessLIFE version 1.0. For both the alloys and the welds, the classes of materials covered in this version of the software include low carbon steels, medium carbon steels, chrome-moly steels, austenitic stainless steels, superaustenitic stainless steels, duplex stainless steels, superduplex stainless steels, nickel-chromium alloys, nickel-molybdenum alloys, nickel-chromium-molybdenum alloys, and nickel-copper alloys, among others. Figure 28 shows another feature that enhances the user-friendliness of the AssessLIFE software. On mouseover of the alloy configuration box, a popup of the assembly selected for analysis is displayed. This feature enables the user to visualize the assembly as they enter the alloy and weld user data.

The selection of an alloy or weld filler metal will call out its mechanical properties in Figure 29. The user can edit the mechanical properties of the alloy or weld filler metal to account for real-life processes that alter the mechanical properties of the materials such as heat treatment and other metal working processes. While the mechanical properties of alloys and welds may not generate significant contributions to corrosion degradation, which proceeds via chemical means, some mechanical properties do contribute significantly to erosion, metal fatigue, and corrosion fatigue degradation processes. As shown in Figure 30, The “Corrodent” input window succeeds the mechanical page. In this page in version 1.0 of the AssessLIFE software, the corrodent dropdown list contains steam, water, chloride solution, hydrochloric acid, hydrobromic acid, hydrogen sulfide, sulfuric acid, nitric acid, phosphoric acid, chromic acid, acetic acid, and formic acid. Furthermore, the oxidizer or accelerant dropdown list includes oxygen, ozone, fluorine, bromine, iodine, hypochlorite, chlorate, sulphur dioxide, dichromate, permanganate, manganate, ferric chloride, and ferrous chloride.

Figure 31 shows that the “process” window succeeds the “corrodent” page. In the process page, the user inputs the service process parameters such as fluid velocity, temperature, pH, and pressure. The last input window in the software for the “wet corrosion” degradation mechanism is the “size & thicknesses” window. Here, the user enters the physical dimension of the asset or assembly. The

next window, (Figure 33) or the “Analyze” window, contains the “Analyze” button with which the software analysis is initiated.

Figure 25. The AssessLIFE software: “InfoPage” read-only window

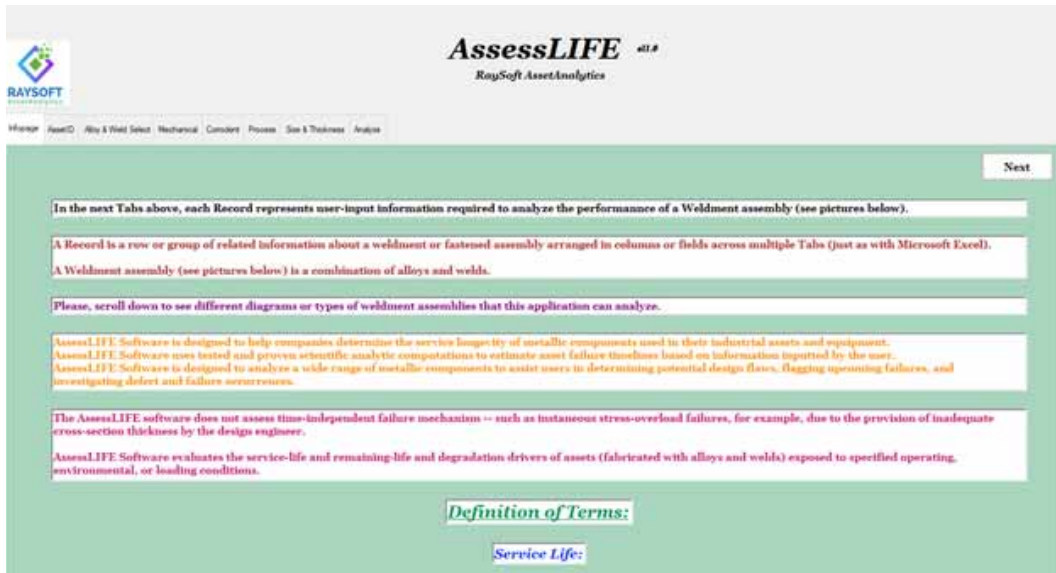


Figure 26. The AssessLIFE software: “Asset ID” input window



Figure 27. The AssessLIFE software: "Alloy and Weld Select" input window

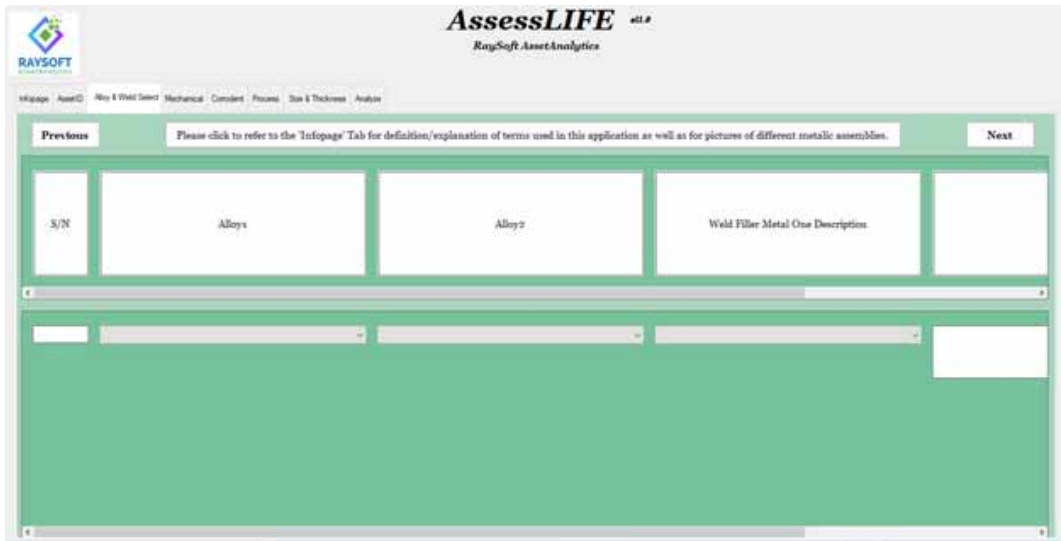


Figure 28. The AssessLIFE software: "Alloy and Weld Select" input Window with popup of assembly assessed

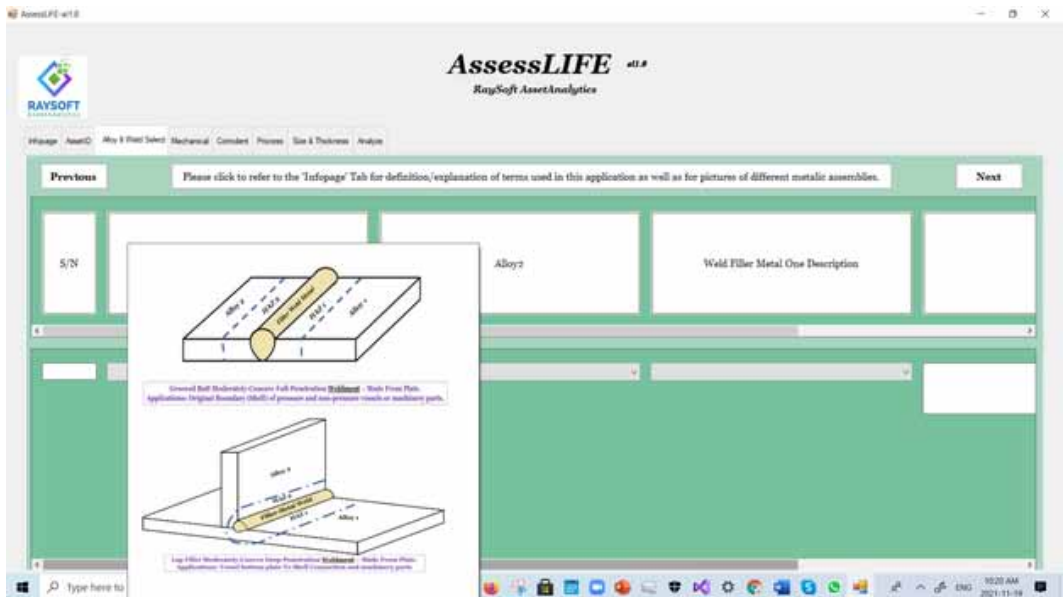


Figure 29. The AssessLIFE software: “Mechanical” properties display window

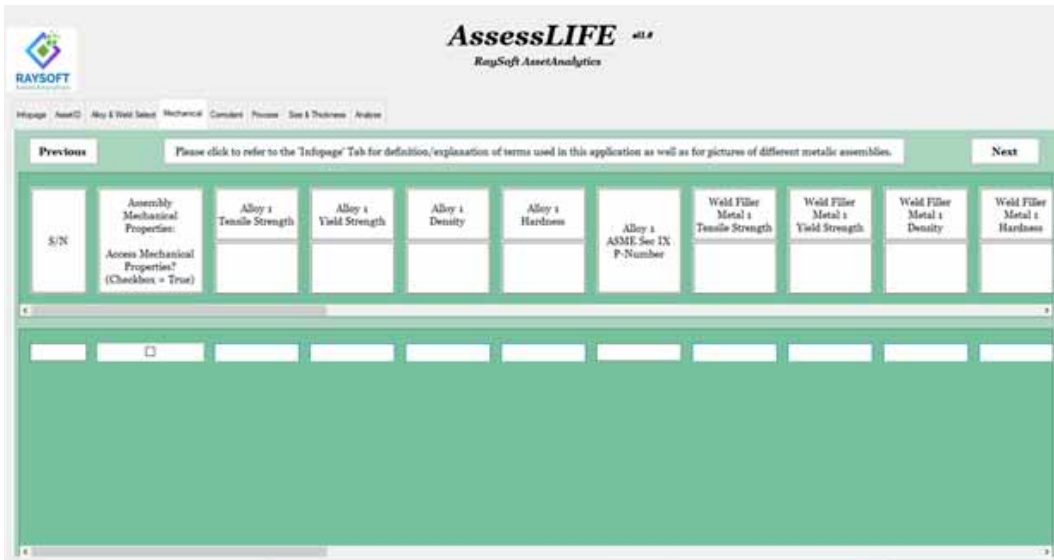


Figure 30. The AssessLIFE software: “Corrosion” properties input window



Figure 31. The AssessLIFE software: “Process” properties input window

Please click to refer to the 'Helppage' Tab for definition, explanation of terms used in this application as well as for pictures of different metallic assemblies.							
S/N	Stream Operating Pressure	Combined Pressure = (Mechanical Pressure Via Weight on Elements + Stream Operating Pressure)	External Pressure	Stream Average Velocity	Stimulate Local Turbulence? (Checkbox = True)	Stream pH	Stream Temperature
<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="checkbox"/>	<input type="text"/>	<input type="text"/>

Figure 32. The AssessLIFE software: “Size & Thickness” input window

Please click to refer to the 'Helppage' Tab for definition, explanation of terms used in this application as well as for pictures of different metallic assemblies.											
S/N	Alloy 1: Thickness	Alloy 1: Thickness Resisting Pressure	Alloy 2: Thickness	Alloy 2: Thickness Resisting Pressure	Change Design Safety Factor? (Checkbox = True)	Design Safety Factor	Alloy 1: Add Corrosion Allowance? (Checkbox = True)	Alloy 1: Corrosion Allowance	Alloy 2: Add Corrosion Allowance? (Checkbox = True)	Alloy 2: Corrosion Allowance	Alloy 1: Total Thickness
<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="checkbox"/>	<input type="text"/>	<input type="checkbox"/>	<input type="text"/>	<input type="checkbox"/>	<input type="text"/>	<input type="text"/>

Figure 33. The AssessLIFE software: “Analyze” command window



SIMULATED RESULTS AND ANALYSIS

The AssessLIFE software can simulate many practical real-life degradation scenarios. Two scenarios are demonstrated.

AssessLIFE Software: The Effect of Oxygen on the Uniform Corrosion of Carbon Steels in Chloride Solution

Table 1 shows the parameters with which to simulate the wet corrosion degradation of a carbon steel alloy in chloride solution. Alloy “A” is identical to Alloy “B.” They are subjected to identical service conditions, except for the oxygen exposure conditions. The AssessLIFE software simulates the degradation via the “wet corrosion” degradation mechanisms and generates the results shown in Figure 34, Figure 35, and Figure 36.

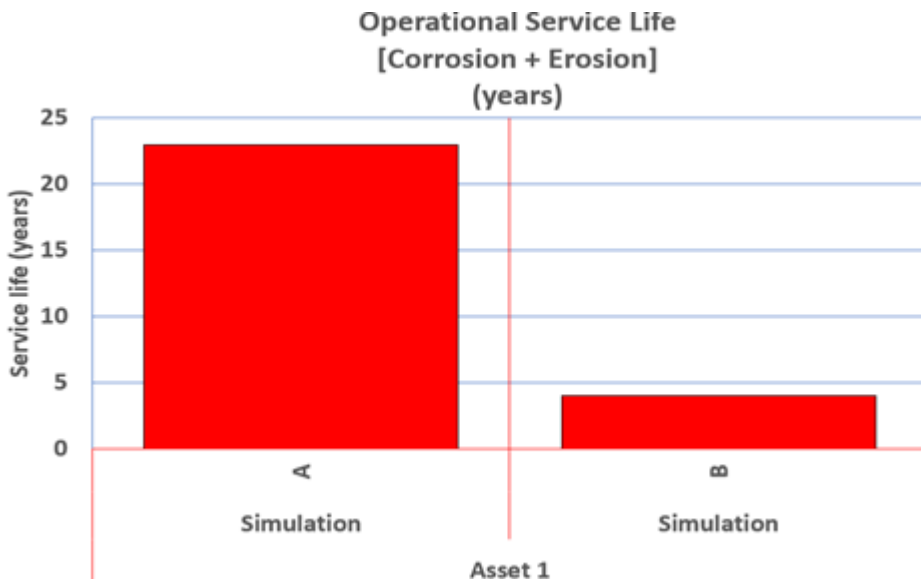
Table 1. Parameters for carbon steel corrosion simulation

Carbon steel alloy	Oxygen (ppb)	Temperature (C)	pH	Flow Velocity (m/s)	Chloride conc (wt%)	Thickness (mm)
A	20	50	8	1.0	3	9.5
B	15000	50	8	1.0	3	9.5

From Table 1, the identical carbon steel alloys “A” & “B” are exposed to identical service conditions – except for the oxygen concentration exposure difference between the two alloys. Carbon steel alloy “A” was exposed to 20 ppb in contrast to the 1500 ppb to which carbon steel alloy “B” was exposed. Figure 34 shows that this difference in oxygen exposure concentration reduced the expected lifespan of carbon steel alloy “B” from 23 to 4 years – more than a 90% reduction in the lifespan of the carbon steel. Hence, the AssessLIFE software provides great safety, technical, and financial benefits by providing the lifespan analytics and other high-value analytics for its users and enhances their decision-making capabilities. The analytics from Figure

35 and Figure 36 show that an increase from 20 ppb oxygen exposure to 1500 ppb (or 15 ppm) increased the oxygen contribution (the fourth box from the left) of the corrosion rate of carbon steel alloy from 0.01 mm/year degradation rate to 2 mm/year degradation rate – which is a 200% increase in the degradation rate of the carbon steel alloy. Furthermore, the lifespan of alloy “B” decreased from 23 years to 4 years – which represents a 475% decrease in the lifespan of an identical alloy exposed to identical conditions (such as alloy “A”), except for exposure to 20 ppb of oxygen concentration. Similar degradation rates were generated by multiple researchers who investigated the corrosion of carbon steel alloys exposed to similar environmental conditions (Do et al., 1994; Mobin et al., 2011; Priyotomo et al., 2017). Therefore, by employing tested and proven scientific analytical computations, forecasting, prediction, and analytics, the AssessLIFE software possesses the capabilities to significantly reduce the billions of dollars expended in assets that degrade prematurely, enhance personal and asset safety, and generate financial benefits for its users.

Figure 34. AssessLIFE software: Simulated lifespan (in years) of carbon steels “A” & “B” simulated in chloride solution



AssessLIFE Software: The Effect of Flow Velocity on The Pitting Corrosion of 316L Stainless Steels in Chloride Solution

Table 2 shows the exposure parameters of two identical 316L stainless steel alloys exposed in a saturated chloride solution. The exposure parameters for the two alloys are identical – except for the flow velocity on alloy “A,” which is 0.5 m/s, in contrast to the 2.0 m/s flow velocity on alloy “B.” The user of the AssessLIFE software inputs these parameters into the software user interface and simulates the pitting corrosion attack via the “wet corrosion” degradation mechanism. Figure 37 shows that by increasing the flow velocity on the alloys from 0.5 to 2 m/s, the lifespan of the 316L alloy increased from 2 to 26 years. It is postulated that the increased flow velocity increased flow turbulence at the alloy-fluid interface. Greater flow turbulence acts to scour the surface of the alloy and disrupts the embedment of chloride into the alloy. Since the embedment of chloride into the alloy typically progresses pitting corrosion attack, the higher fluid velocity, which disrupts the chloride embedment process, ultimately extends the lifespan of the alloy. Similar results were obtained by Wharton and Wood (2004), who investigated the influence of flow conditions on the corrosion of AISI 304L stainless steel in chloride media. The authors noted that “stable pitting was most evident

during the laminar flow regime immediately before the transition [to turbulent to flow] and near the critical velocity of ($\sim 1.5 \text{ ms}^{-1}$). Above the critical velocity the viscous sublayer can be considered thin enough for high-speed fluid (sweep events) to penetrate across it, to the metal surface, with sufficient kinetic energy to disturb the growth of metastable pitting, thus impeding the growth of stable pits.”

Figure 35. AssessLIFE software result: Simulated degradation driver contribution (mm/yr) of carbon steels “A” & “B” in chloride solution

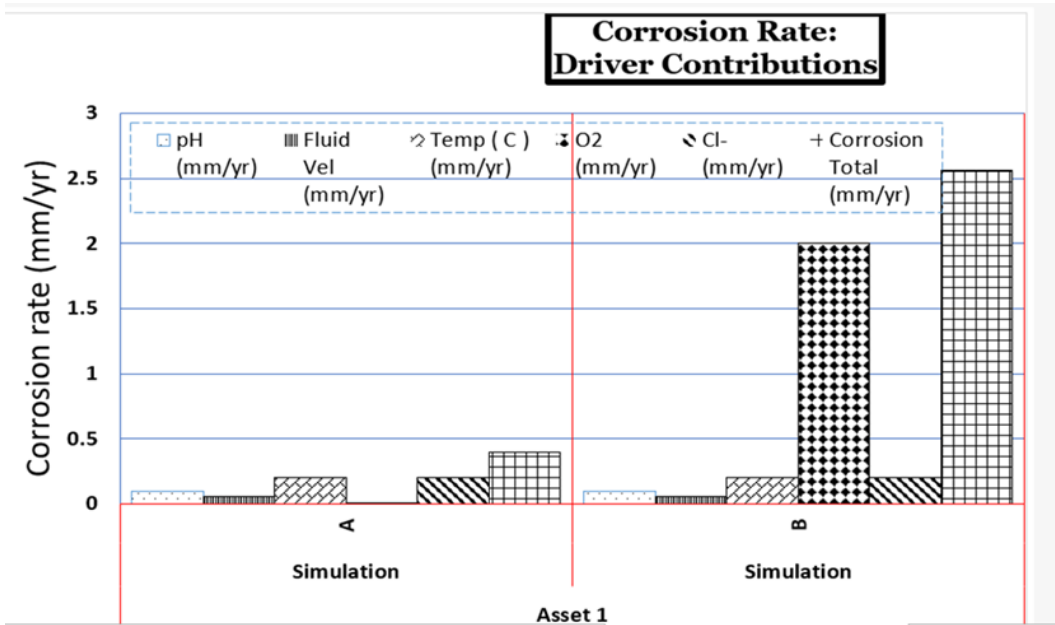


Figure 36. Rescaled version of Figure 35

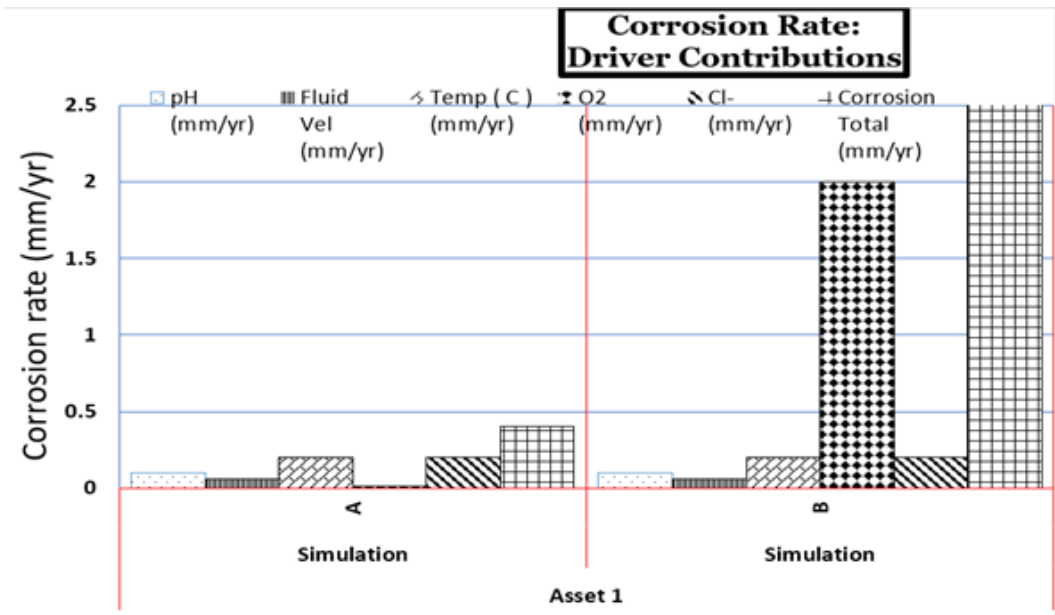
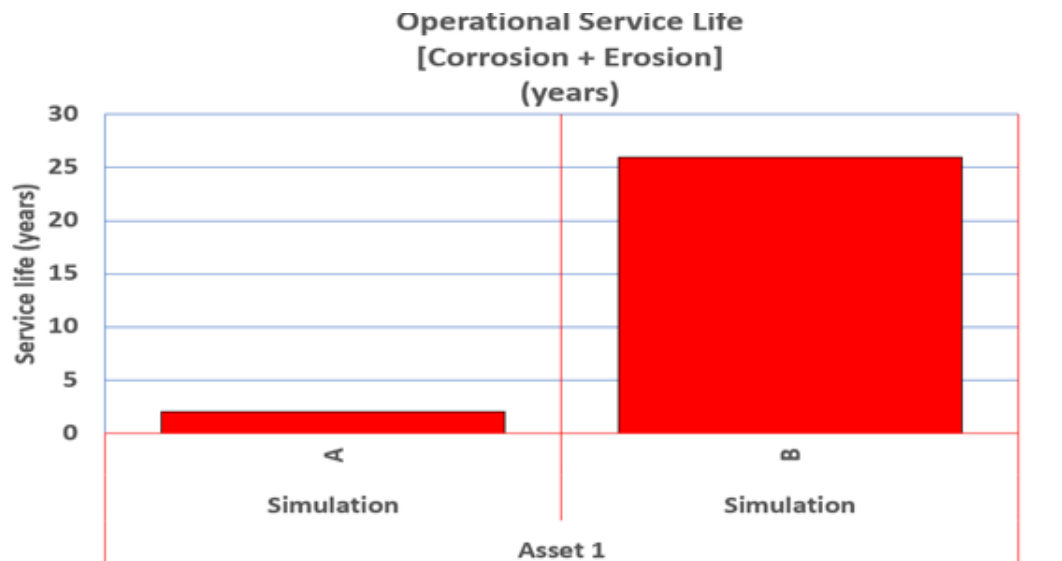


Table 2. Parameters for stainless steel corrosion simulation

316L Stainless steel alloy	Oxygen (ppb)	Temperature (C)	pH	Flow velocity (m/s)	Chloride conc (wt %)	Thickness (mm)
A	15000	50	8	0.5	20	3.4
B	15000	50	8	2.0	20	3.4

Figure 37. AssessLIFE software result: Simulated degradation driver contribution (mm/yr) of Stainless steels “A” & “B” in chloride solution



CONCLUSION

This paper has proposed AssessLIFE software to address the strategic deficiency arising from the continuous degradation of metallic industrial assets, equipment, and components, which often results in crumbling infrastructure, and thus requires industries to expend billions of dollars on mitigation strategies. The proposed software has the potential to enhance personnel safety in physical asset management by generating diagnosis and analytics on asset lifespan and health status. Alloy degradation costs the global economy billions of dollars a year. By employing tested and proven scientific analytical computations, forecasting, prediction, and analytics, AssessLIFE software plans to significantly reduce the billions of dollars wasted as the cost of alloy degradation as well as reduce the billions of dollars expended via inspection, treatment, and repair of degradation-prone assets and infrastructure. AssessLIFE software estimates asset lifespan and other analytics via mathematical modeling, integration, and automation, and then provides various industry stakeholders with useful information to make better decisions in areas of industrial asset management.

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