# Fault Tree Analysis for Fungal Corrosion of Coated Aluminum

Sandeep Chawla,* Joe Payer,‡,** and Carla Giai**

## ABSTRACT

*A fault tree methodology has been used to analyze the combinations of basic factors involved in fungal degradation and corrosion. The purpose was to demonstrate the identification of mitigation actions for reducing the risk of fungal corrosion of coated aluminum in aircraft. The interaction between fungal-induced degradation processes and coatings is described, and the methodology of the fault tree analysis (FTA) is presented. The interconnection of the basic factors through conventional AND and OR logic gates in the fault tree structure reveals vulnerabilities and potential failure pathways in the system. Mitigation actions can be directed at these basic factors to reduce or eliminate failure pathways, thereby reducing the overall risk of fungal-induced corrosion. Potential applications of FTA for corrosion mitigation, design and materials selection, and failure analysis are presented.*

*KEY WORDS: aluminum, coatings, fault tree, fungal corrosion, risk*

## INTRODUCTION

Fault tree analysis (FTA) is a risk management tool that is used in reliability studies, safety analyses, and accident investigations of complex systems; however, FTA is not frequently used in corrosion risk management. A fault tree is a diagrammatic representation of a system starting from a top undesirable event with combinations of more basic, lower level factors, events, or failures. The use of FTA methodology is demonstrated for qualitatively analyzing the combinations of factors that could result in the top event, i.e., fungal degradation and corrosion of coated aluminum in aircraft. The objective is to demonstrate the identification of failure pathways and mitigation actions for reducing the risk of fungal-induced corrosion. The possible mitigation actions have been classified into five categories: maintenance, design, coating development, testing, and research.

In the following, the interaction between fungal-induced degradation processes and coatings are described. Then, the methodology of FTA is presented. The interconnection of the basic factors through conventional AND and OR logic gates in the fault tree structure reveals vulnerabilities and potential failure pathways in the system. Mitigation actions can be directed at these basic factors to reduce or eliminate failure pathways and thereby reduce the overall risk of fungal-induced corrosion. To demonstrate useful applications of FTA, illustrations are presented for corrosion mitigation, design and materials selection, and failure analysis.

## INTERACTION BETWEEN FUNGAL-INDUCED DEGRADATION PROCESSES AND COATINGS

The terminology of "fungal-induced" and "fungal-influenced" degradation and corrosion are used in the literature where fungi contribute to the degradation of coatings and corrosion of metals. Here, we primarily use the term fungal-induced corrosion. The interac-

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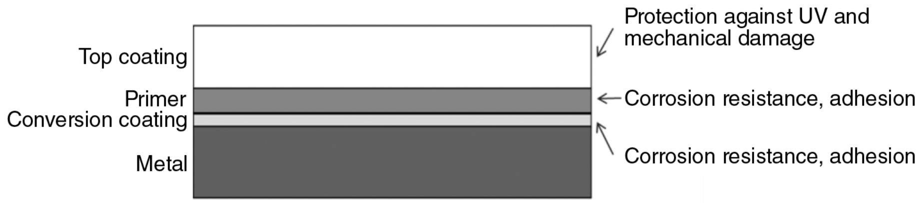


**FIGURE 1.** *Schematic of section of a typical multilayer aircraft coating.*

tion between fungal-induced degradation processes for coatings and fungal-induced corrosion of metals is complex. Background information is presented for:

—aircraft coatings
—fugal contamination in aircraft
—biofilm formation
—fungal-influenced degradation of bare and coated metal
—fungal degradation of military equipment

The objective is to provide perspectives and note the interplay among processes. An exemplar of the need for better understanding is the broad introduction of non-Cr coatings. The interplay between microbial-induced corrosion and non-Cr coatings has not received much attention in the literature. This has huge implications for the military and presents a major challenge for corrosion mitigation programs.

## Aircraft Coatings

In commercial and military aircraft, surface coatings are used for aesthetics, environmental protection, and other special functions. Coatings are applied on aircraft skin and structurals made from bare and clad variants of aluminum alloys such as AA2024 (UNS A92024),[(1)] AA6061 (UNS A96061), and AA7075 (UNS A97075). These coatings usually consist of one or more of the following layers to meet operational requirements:

—a conversion coating, which is a surface treatment applied directly to the aluminum alloy surface, typically producing an oxide or hydroxide that improves corrosion resistance and adhesion
—an epoxy-based primer that further enhances corrosion resistance and improves adhesion of the topcoat
—a hard topcoat, typically polyester polyurethane, that protects the primer from UV and mechanical damage

Various additives in the formulation of these layers are used to facilitate coating application and impart other functional properties. A schematic of a typical multilayer aircraft coating, known as a stack-up, is illustrated in Figure 1. Coatings are generally qualified to commercial and military specifications. Chemical conversion coatings for aluminum alloys are thin, tenacious films produced by the chemical reaction of the metal surface with an active chemical species. For example, in military aircraft applications, conversion coat thickness is typically specified in terms of weight gain of test panels (e.g., greater than 107.5 mg/m$^2$).[1-2] The primer coat is usually an epoxy polyamide formulation with a dry film thickness (DFT) of 15 μm to 23 μm.[3] The top coat is a polyester polyurethane formulation with a DFT of 43 μm to 58 μm.[4] Aircraft coatings experience a variety of environmental and mechanical stresses depending on the aircraft type, mission, and operating conditions.

## Fungal Contamination in Aircraft

Fungi are non-photosynthetic heterotrophic organisms. They exhibit threadlike vegetative growth known as hyphae from single cells or spores; masses of hyphae form a mycelium. Fungi are ubiquitous, especially in hot, humid environments, and have been found on virtually all interior surfaces of military and commercial aircraft. They assimilate organic material producing organic acids through metabolic processes. Presence of fungi in aircraft has been associated with adverse health effects for air crew and passengers, unaesthetic appearance of surfaces, degradation of protective coatings, corrosion of underlying metal, and high cost of maintenance.[5]

In a study of 10 helicopters at various stages of depot maintenance by Little and others,[6] sampling of bilges, bulkheads, and fluids showed several different fungal genera. These included *Pestalotia, Trichoderma, Epicoccum, Phoma, Aureobasidium, Stemphylium, Penicilium, Hormodendrum, Fusarium, Aspergillus, Alternaria, Nigrospora, Phialomyces, Mucor,* and *Phoma*.

Little variation of the species was observed despite operation of aircraft in different geographic locations.

## Fungi as Inducers of Corrosion

Fungi have been identified as influencing deterioration processes in a number of materials. In addition to playing a fundamental role in decomposition processes in terrestrial ecosystems, fungi are also responsible for the degradation of man-made materials.[7] There is extensive evidence of fungal degradation of metals.[5-18] Similarly, there is extensive evidence of fungal degradation of polymeric materials.[5,14-15,19-23]

[(1)] UNS numbers are listed in *Metals and Alloys in the Unified Numbering System*, published by the Society of Automotive Engineers (SAE International) and cosponsored by ASTM International.

Deterioration processes influenced by microorganisms are, in general, attributed to their ability to form biofilms when in contact with surfaces in aqueous media.[13,19,24-26] Biofilms are complex structures consisting of aggregated microbial cells, exopolymers, and particulate matter that provide microorganisms with shelter and nutrients, and protect them from desiccation and other adverse environmental conditions. Their formation involves communication among bacterial and fungal cells, as well as their interaction with chemical and physical characteristics of the surface in which they develop.[24,27-31]

### *Biofilm Formation*

Most of the literature on biofilms and their effects on metals relates to bacterial-dominated biofilms. Fungal biofilms, on the other hand, have been extensively studied in the biomedical field, especially for the pathogen *Candida albicans*.[31-33] However, there are similarities between bacterial and fungal biofilm formation processes,[34-35] as well as their influence on corrosion.[11,25-26]

Biofilm formation, for both bacteria and fungi, involves a series of stages that can be summarized as follows. In the initial step, compounds dissolved in water are adsorbed into the surface and planktonic, i.e., free, living, microorganisms reach the surface and start to become attached to it. The degree of adhesion depends on physiological characteristics of the microorganisms, nutritional status, growth phase, physicochemical characteristics of the medium in which the microorganisms dwell, and nature of the surface. There is evidence that in some bacterial biofilms some bacteria become non-motile, or sessile, while another fraction remains motile. The coexistence of both populations represents an advantageous characteristic should environmental conditions change.[36] Production of extracellular polymeric substances (EPS) also becomes crucial at these stages.[28,35]

Once the microorganisms are attached to the surface, they start multiplying. The biofilm grows by microbial reproduction, planktonic cells settlement, and the continuous production of EPS. At this point, it is likely that more than one species of bacteria or fungi will be present, and these microorganisms will be spatially distributed in the biofilm exploiting microenvironments generated by the interaction of microbial species within the biofilm.[28,35]

Finally, parts of the biofilm start to slough-off, probably as a response to different stimuli. For example, this could be related to the film reaching a critical thickness that cannot resist shearing forces present in the systems. Removal of parts of the biofilm can also occur as a response to nutrient unavailability for some of the microorganisms within the biofilm. In any case, removed parts of the biofilm can reach other areas on the surface, contributing to the spread of the biofilm on the system.[28,35]

It is important to note that fungal biofilms have been shown to be formed not only by a mixture of cells and extracellular compounds—much like bacterial biofilms—but also by hyphae, i.e., the filamentous structures formed by apical growth. For *Candida albicans* biofilms, this mixture of morphologies is only observed when the organisms are grown in contact with a surface.[33]

### *Fungal-Influenced Degradation Mechanisms: Bare Metals*

Microorganisms, in general, can influence degradation of bare metals through direct effects on cathodic or anodic processes, changes in surface film resistivity by metabolites and exopolymeric materials, and/or the generation of microenvironments promoting corrosion, for instance by creating low oxygen concentration and acidic microenvironments or the establishment of ion concentration cells.[13,37]

Several studies have attempted to elucidate the mechanistic nature of the degradation of bare metals by fungi. For instance, Clark and others[8-9] investigated the solubilization and accumulation of metals by fungi. Their studies found evidence that the mere physical contact of fungi with thin foils of several metals, including aluminum and stainless steel, was not enough to promote metal dissolution. Instead, fungal metabolites played a critical role in the degradation of the metals.

Similarly, Belov, et al., analyzed the effects of eight strains of mitosporic fungi on corrosion.[11] Mitosporic fungi comprise a large and heterogeneous group of fungi whose common characteristic is the absence of a sexual state. The effects on corrosion of pure aluminum and its alloys were studied with focus particularly on the initial stages of the degradation processes.[11] In their study, Belov and coauthors found that within the first 5 to 20 days, all fungi produced an exudate with pH ranging from 7 to 10.[11] The timing of exudate production and its pH varied with the considered strain and the metal surface on which the fungi where exposed. Independently of that, all exudates contained no aluminum ions, but sodium and potassium ions were commonly present. After some time (ranging from days to less than two months), the accumulated exudates converted into a "jelly-like substance." The transformation was accompanied by a neutralization of the medium and its enrichment in alumina ($Al_2O_3$) and aluminum hydroxide ($Al[OH]_3$). Two months after fungal inoculation, corrosion of the metal was evident. The accumulated corrosion products were rich in oxide aluminum compounds. One month later, aluminum oxides accounted for at least 80% of the corrosion products; however, at this point, a fraction of organic acids of fungal origin made up for the rest of the corrosion products. The most relevant aspect of the entire process was that fungi mycelia, i.e. the fungal body, played a fundamental role in selectively exchanging and concentrating ions necessary to maintain their metabolic requirements.

### *Fungal-Influenced Degradation Mechanisms: Coated Metals*

When considering coated systems, four basic conditions need to be met to promote microbial growth. First, there must be sufficient moisture, which in the case of fungi, could be a water activity value as low as 0.60.[15,38,(2)] Second, temperature needs to be maintained within optimal ranges for each microorganism, which can be as broad as the range at which water can exist in the liquid phase.[39] Third, there must be organic material available that could be utilized as nutrient. Organic material could be derived from the components of the coating itself or from other external sources. These external sources include dust and other materials accumulated on the coating as a result of normal use/storage, or other organisms dwelling on the coated surface such as certain algae. Fungal mycelia act as an anchor for the fungi to the surface, but can also provide shelter for other organisms.[40] Additionally, the vegetative growth of fungi allows for nutrient scouting throughout the surface, i.e., strands are formed that extend along the surface in search of more nutrient. This combined with the fact that fungal requirements for elements such as nitrogen are lower than those for bacteria increases considerably the success of fungi colonization of any surface.[38] Finally, there must be an absence of microbiocidal agents. For instance, it is well known that certain corrosion inhibitors commonly used in primers have biocidal properties.

Even though it is widely accepted that fungal production of organic acids as secondary metabolites has a relevant role in direct metal corrosion, there are several hypotheses regarding other mechanisms for fungal-influenced corrosion of coated metals.[5-9,11,13,37] For example, it is proposed that corrosion in such systems can occur as an indirect consequence of fungal consumption of compounds used in solution such as corrosion inhibitors or polymers used as protective coatings for metals.[14,19-23,37,39,41-42] In the case of polymeric coatings, there are some differences in terms of susceptibility to fungal degradation. Susceptibility reflects either the relative ease with which fungi can extract carbon from the coating—the polymer resin or the organic additives—for nutritional purposes or enzymatic attack of coating due to secreted enzymes as part of the normal metabolic processes of fungi. For instance, polyester-type polyurethanes have been found to be more susceptible to fungal attack than polyether polyurethanes.[43-44] Mechanistically, polyurethanes are degraded by the action of at least two fungal extracellular enzymes identified as esterases: one of the enzymes hydrolyses the polyurethane molecule at the polymer chain, whereas the other removes monomer units from the chain end.[45-47] However, it must be noted that studies on the mechanisms of polyurethane degradation by fungi have usually been done with the polymer in some form of solution and not as an applied coating.

Degradation of coated systems can also occur because extraneous substances on the coating, such as dust, lanolin, hydraulic fluids, etc., can be used as nutrients by fungi, promoting their growth and subsequent damage to the coating.[48] Moreover, fungi growing on coated systems can create environments suitable for other microorganisms. For example, heavy fungal growth can form anaerobic regions in the biofilm that can be colonized by sulfate-reducing bacteria, microorganisms that are known to significantly influence corrosion processes.[40]

Additionally, the use of unapproved cleaning agents and procedures can sometimes lead to problems. For example, it has been reported that bleach was occasionally used to lighten dark spots on the coating that had not been removed during regular cleaning. In those cases, the bleach itself damaged the coating, exposing the metal to fungal action.[5]

### *Fungal Degradation of Military Equipment: Coated Aluminum Systems in Aircraft*

Until recently in the aircraft industry, the most widely used corrosion inhibitors in conversion coatings and primers were based on chromates.[49] Despite the extensive use of chromate-based corrosion inhibitors and their efficacy in preventing coated metal degradation, there are strong pressures to replace them because of health and environmental concerns.[23,49-51] The introduction of non-Cr coatings has huge implications for the military, but the interplay between microbial-induced corrosion and non-Cr coatings has not received much attention in the literature.

Fungi have been identified as responsible for the degradation of military equipment, especially in humid environments.[5,39] There is extensive literature on the degradation of aircraft fuel storage tanks.[17-18,52-53] There are also several studies on fungal degradation of painted aircraft interiors.[5,14-15,23,40] In all studied cases, which included fungal strains isolated from actual aircraft interiors, fungi have been related to the direct degradation of coating systems and/or the corrosion of underlying metals.

In addition to imparting outstanding corrosion inhibition properties to the coating, chromates have been identified as biocides. The search for and validation of corrosion inhibitors in primers that have effective biocidal properties comparable to chromates is an area of active research. Stranger-Johannessen determined the efficacy of zinc chromate to prevent fungal degradation of painted steel plates.[41] Thorp and others also investigated the role of chromate pig-

[(2)] Water activity of 1 corresponds to pure water. Most bacteria require a water activity of 0.80 or higher to grow, i.e., 80% of that for fully saturated air.

ments as biocides.[22] Using polyamide-based primers with and without barium chromate as inhibitor, they exposed panels of AA7075 to salt fog for a minimum of 12 weeks. Some of the panels were inoculated with bacterial and fungal strains. After 12 weeks of exposure, panels without chromate in their primers that had been inoculated with the microbial consortium showed the highest corrosion.[22] Biocidal action of chromium was further confirmed by titration of hexavalent chromium against a microbial consortium and a monoculture of *Pseudomonas aeuriginosa* ATCC 6135;[(3)] however, chromium toxicity was effective only for 22 days for pure cultures and 40 days for mixed ones. Although the mechanism for the eventual microbial resistance to chromates was not investigated further, the results were an important design consideration for corrosion inhibitors.[22] In a similar experiment, Trick and Keil found that panels of AA7075 coated with primers containing chromates showed less corrosion when inoculated with bacterial and fungal consortia than panels coated with a non-chromate primer.[23] On the other hand, panels treated with both non-chromate primer and biocides showed corrosion rates similar to panels with the chromate-based primer.[22] Unfortunately, there seem to be no systematic studies on the effect of new coating systems on fungal growth.

Researchers from the Naval Research Laboratory have carried out extensive studies on fungal corrosion in military aircraft.[14,40,48] In addition to showing the extent of fungal contamination on aircraft, and the economical and health-related consequences of fungal presence in helicopters, these studies have provided evidence regarding the chemical nature of coatings and their susceptibility to fungal damage. For instance, Lavoie and Little studied fungi associated with discoloration and growth on interior surfaces of H-46 and H-53 helicopters to evaluate potential biodegradation on typical aircraft surfaces.[40] Even though they found several genera of fungi in all examined aircraft, not all the fungi were actively degrading painted surfaces. Electrochemical tests suggested that at least two of the considered strains were capable of corroding aluminum.[40] Aggressiveness tests on painted coupons exposed for 30 days showed that lacquer-coated coupons had a higher susceptibility to fungal degradation than polyurethane-coated coupons. Degradation of lacquer coatings was in the form of blistering and accumulation of corrosion products at the site of fungal colonization. It was suggested that the difference in the two coatings was probably a result of their dissimilarity at the micro-relief scale since lacquer-based coatings were more porous than polyurethane-based coatings.[40] The authors did acknowledge that longer exposure times could result in fungal degradation of polyurethane-based coatings as well.

[(3)] American Type Culture Collection (ATCC), 10801 University Blvd., Manassas, VA 20110.

In a later study, Lavoie and others determined the short-term effects of fungal growth on AA2024-T6 coated with polyester-polyurethane-based and lacquer-based paints. In both cases, a chromate-based primer was used.[14] After 30 days of exposure, the results were similar to the previous study,[40] with lacquer-based coatings showing higher fungal damage than polyurethane-based coatings. Even though the authors observed some spatial relationship between fungal presence and corrosion products in scratched areas exposed to fungal strains, the data did not support conclusively a causal relationship.[14] No indication of fungal damage on the primer was mentioned in the study.

Little, et al., analyzed the effectiveness of cleaning procedures in reducing the likelihood of fungal damage in both freshly applied and aging (more than 2 years old) aircraft coatings.[48] The study was conducted on coupons prepared to simulate the surface condition of helicopter interiors during field (before and after cleaning) and storage conditions. This included contamination with hydraulic fluids, recent cleaning, and coverage with lanolin-based preservative, respectively. Chromate-based conversion coating and primers were used in all coupons. The topcoat was polyurethane with either a glossy or a flat finish, and a choice of three fungicides added to the coating formulation. A fourth series of control coupons contained no fungicide. The total time of exposure to the fungal strains was 110 days. Aged coatings showed colonization in all cases as early as 18 days. Glossy polyurethane control coupons were colonized earlier than flat controls, which only showed fungal contamination after 110 days of exposure on the areas with hydraulic fluid or lanolin. Biocide additions gave mixed results. Cleaning procedures performed on the most heavily contaminated coupons after the experiment was completed showed that authorized cleaning protocols were not adequate to remove fungal hyphae penetrating the coating, failing to prevent any future, potential fungal degradation. Indeed, after 45 days of cleaning, hyphal regrowth could be observed on the coupons. As with the previous studies reported by this group, no evidence of fungal damage to chromate-based conversion coatings or primers was mentioned. The fungal damage seemed to be restricted to the top coat or other areas where bare aluminum was exposed after scratching, the latter being damage quite commonly encountered in aircraft during their normal use in the field.

## METHODOLOGY FOR FAULT TREE ANALYSIS

This section presents a description of FTA and determination of minimal cut sets. Each minimal cut set identifies a pathway that will result in the undesirable top event. The methodology of FTA is applied to the analysis of fungal degradation of coatings and fungal-

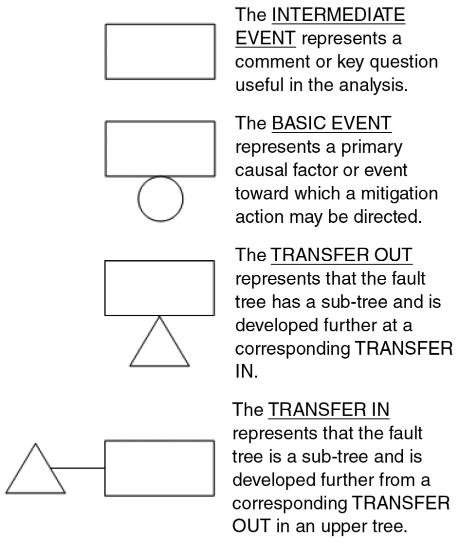


**FIGURE 2.** *Fault tree symbol notation for events.*

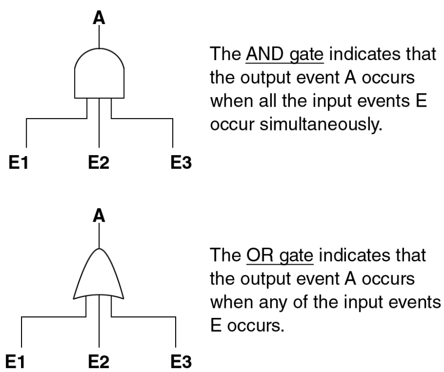


**FIGURE 3.** *Fault tree symbol notation for basic logic gates.*

induced corrosion of coated aluminum. Minimal cut set analysis was used to determine circumstances of pathways leading to the presence of a fungal biofilm on the coating or metal surfaces.

### *Description of Fault Tree Analysis*

FTA is a formalized, event-based risk analysis technique.[54-55] It provides a structured methodology to analyze adverse events in terms of causal factors or lower-level events. Various types of logic gates and special notations are used to depict the hierarchical inter-relationships between these basic causal factors. The conventional event and gate notations used in this work are described in Figures 2 and 3, respectively. There is often no unique way to construct a fault tree. The level of detail depends on the purpose of the fault tree and is determined by the information available on the lower-level or basic events. Fault trees are useful in design-for-risk engineering for identifying system vulnerabilities, and in reliability and safety analysis, and accident investigations.

The application of fault trees to the study of corrosion problems has been illustrated in a few studies. Sridhar mentions a fault-tree approach for estimating the probability of an ethanol pipe leak by stress corrosion cracking (internal and external) or third party damage.[56] Yuhua and Datao have used a fuzzy fault tree analysis to model failure of oil and gas transmission pipelines by stress corrosion cracking, corrosion thinning, and corrosion fatigue.[57] Roberge describes the construction of an elicitation shell based on fault trees to facilitate transfer of information to expert systems for management of corrosion problems.[58]

A fault tree is a qualitative model but it can be used for quantitative, probabilistic analysis. A major goal of qualitative FTA is to determine minimal cut sets. A minimal cut set is defined as the smallest combination of basic events, which if they all occur, will cause the adverse top event to occur.[59] A minimal cut set is therefore considered an AND gate combination of these critical basic events as shown in Figure 4. The top event in the fault tree, in turn, is considered an OR gate combination of its unique minimal cut sets, each minimal cut set representing a combination of circumstances or pathway, which will result in the undesirable top event. Minimal cut sets highlight vulnerabilities in the system. In general, the order of a minimal cut set (number of basic factors in the cut set) reflects how vulnerable the system is to that combination of events. Higher order or longer cut sets tend to have a lower probability of occurrence and a lower importance because of the greater number of factors involved, a result of the multiplicative property of the AND gate (Figure 4). Similarly, numerous cut sets indicate greater vulnerability, a result of the additive property of the OR gate (Figure 4). Minimal cut set analysis is useful in guiding fault mitigation strategies. Any intervention that mitigates a basic factor in a minimal cut set mitigates the occurrence of the adverse top event as a result of that cut set.

Minimal cut sets are determined by a downward decomposition of the top event through the logic gate structure of the fault tree.[59] Every fault tree can be represented by an equivalent Boolean algebraic expression, which is the combination of its unique minimal cut sets. Another approach used to determine minimal cut sets involves converting the fault tree into a logically equivalent block diagram comprising a series and parallel connections of the basic events/factors. A minimal cut set would then be the smallest combination of blocks that interrupts all possible connections between the input and output points.[60]

Fault trees are also used for quantitative risk assessment with basic event occurrence rates as data inputs to the model. Basic event probabilities are determined from a specified failure distribution. Subjective estimates of probability can also be used. The probability of the top event is computed through algebraic rules of combinations for the logic gates involved. Further, the importance value of each basic event or minimal cut set is calculated and numerically

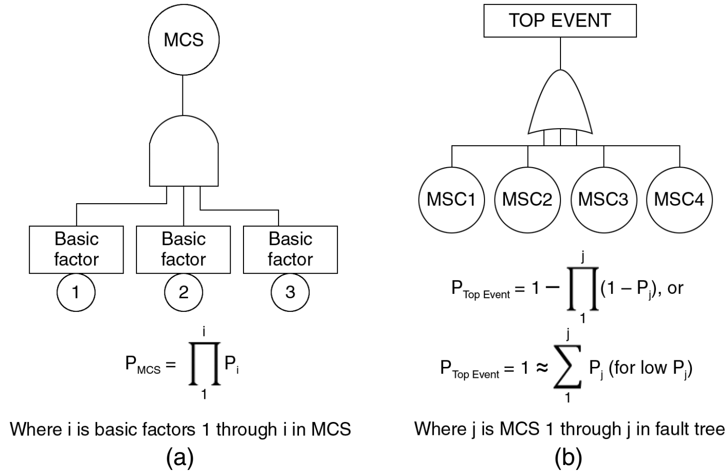


**FIGURE 4.** *(a) The minimal cut set as an AND gate combination of factors sufficient to cause the top event. (b) The top event as an OR gate combination of the minimal cut sets of the fault tree.*

ranked. The importance value can be viewed as the conditional probability that a basic event or minimal cut set occurs given that the top event has already occurred. Importance analysis is useful in prioritizing events for corrective action.

In this work, we have adopted a qualitative FTA approach to identify the minimal cut sets for a section of the fault tree for fungal-induced corrosion of coated aluminum. These minimal cut sets form the basis for suggesting possible interceding or mitigating actions.

## *Fault Tree Analysis of Fungal-Induced Corrosion*

As discussed in the review of literature, fungal-induced corrosion in coated systems involves the formation of viable fungal films on the surface, fungal attack on the coating layers, and fungal-mediated corrosion of the substrate metal. The top adverse event, fungal-induced corrosion of the coated aluminum, depends on two main events: the presence of a viable fungal film and fungal attack on the substrate. Therefore, the overall fault tree (T) can be modeled as a combination of two main sub-trees T1 and T2 related to these aspects as shown in Figure 5. Sub-tree T1 is composed of several lower-level or basic factors that contribute to the formation and presence of a fungal biofilm on the surface (Figure 6). Sub-tree T2 (Figure 7) is modeled as an OR combination of possible starting surface conditions, with an AND combination of sub-trees from T3 through T6, each representing sequential fungal attack on successive layers present in the coated system. Table 1 illustrates the connection between various coating conditions and the combination of sub-trees (pathways) that need to be considered. Corrosion of the underlying aluminum alloy occurs only after each coating layer is breached via fungal or mechanical action. The factors involved in fungal attack on each layer can be analyzed in terms of susceptibility of its organic and inorganic constituents to fungal action and the availability of fungicidal agents. Finally, the factors involved in fungal attack of the exposed aluminum substrate itself are considered. It may be noted that the level of detail in each sub-tree can be extended as more information on the lower level events or factors becomes available.

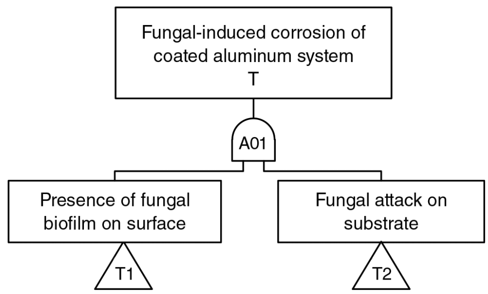


**FIGURE 5.** *Overall fault tree for fungal corrosion of coated aluminum.*

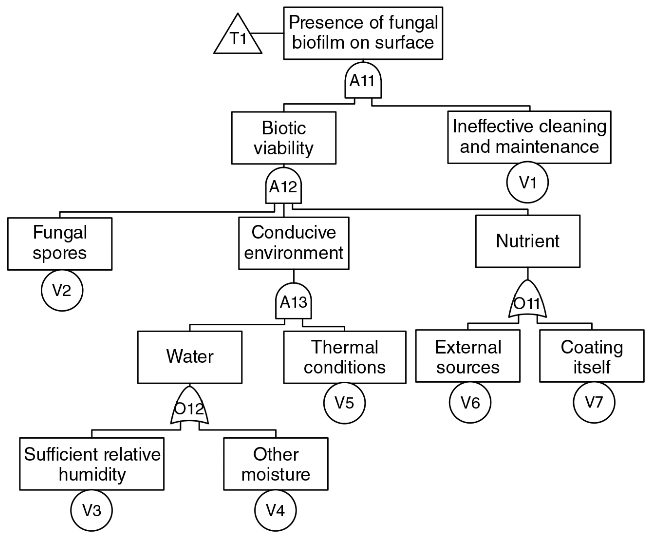


**FIGURE 6.** *Sub-tree T1: fungal biofilm on surface.*

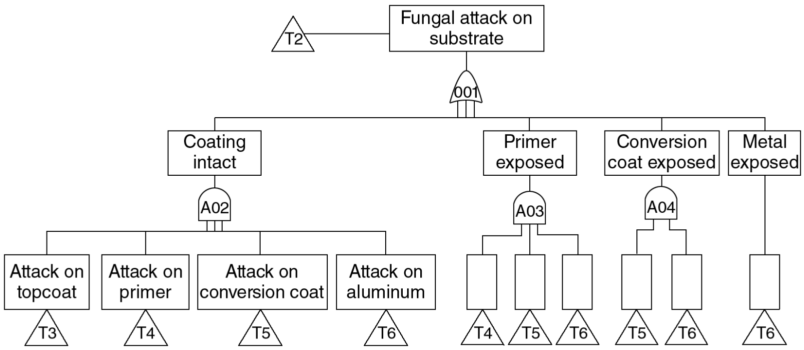


**FIGURE 7.** *Sub-tree T2: fungal attack on substrate.*

**TABLE 1**

*Pathways to Corrosion of the Aluminum Substrate Beneath a Multi-Layer Coating System*

| Necessary Conditions (sub-tree) → / Coating Condition ↓ | Topcoat Degradation T3 | Primer Degradation T4 | Conversion Coat Degradation T5 | Metal Corrosion T6 |
|---|---|---|---|---|
| A Is coating intact? | X | X | X | X |
| B Is primer exposed? | | X | X | X |
| C Is conversion coat exposed? | | | X | X |
| D Is metal exposed? | | | | X |

Coating condition determines the path to be taken.
"Yes" → then follow the path; "No" → then move onto the next path.

The top adverse event for sub-tree T1 is the formation of viable fungal biofilm on the surface, where biotic viability and cleaning are the important issues. Factors that are necessary for the formation, sustenance, growth, and survival of fungal films include the presence of spores, conducive or facilitative environmental conditions, and sources of nutrition as represented through AND gate A12. Optimum thermal ranges for the active genera and the availability of water are the considered environmental conditions. Liquid water is found under humid service and storage conditions of aircraft, or from accumulation in certain areas of the aircraft as a result of improper drainage. Organic nutrient matter may be derived from several external sources including organic residues on the surface (dust, planktonic matter, hydraulic oil, jet fuel, grease, lanolin, etc.), or the polymer in the coating itself can be source of nutrient (gate O11).

Sub-trees T3, T4, and T5 for fungal degradation of each of the coating layers are shown in Figures 8 through 10, respectively. The fault tree for each layer is depicted as a simple combination of the susceptibility of the layer to fungal attack and the ineffectiveness (or lack) of fungicidal action. Susceptibility reflects either the relative ease with which fungi can extract carbon from the coating—the polymer resin or the organic additives—for nutritional purposes or enzymatic attack of coating due to secreted enzymes as part of the normal metabolic processes of fungi. Polyurethane topcoat formulations are susceptible to breakdown by fungal enzymatic processes. This involves hydrolytic breakdown of ester bonds and depolymerization into shorter units (mers, dimers, oligomers) that can be assimilated by the microbes.[47,61-62] Enzymatic attack may also occur on organic additives, e.g., plasticizers, fillers, functional modifiers, in the topcoat.[6] Fungicides and fungistats are important in enhancing resistance to attack.

Not much information is available in the literature on specific mechanisms for fungal attack on primers and conversion coatings. Epoxy primers have been found to undergo more rapid degradation than aliphatic polyurethane when exposed to mixed fungal cultures.[61] Fungicidal action is provided by corrosion inhibitors based on hexavalent chromium, which are incorporated in the primer; however, their effectiveness has been shown to be of limited term.[23] A study by Stropki and others compared fungal growth on chromate versus non-chromate conversion coat formulations, but the susceptibility and mechanisms for fungal degradation have not been explicitly studied.[63-64]

Fungal-induced corrosion of bare aluminum is shown in Figure 11 (sub-tree T6). Once exposed by fungal action (or mechanical breach) on the coating, the substrate metal can undergo corrosion either through non-fungal processes or fungal-mediated processes (gate O61). For fungal-mediated corrosion

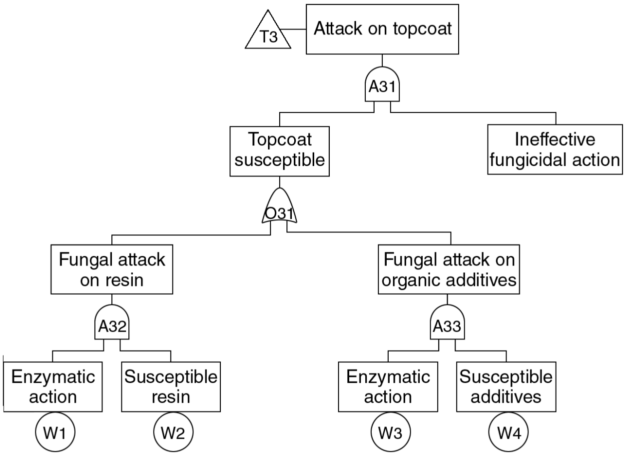


**FIGURE 8.** *Sub-tree T3: fungal attack on topcoat.*

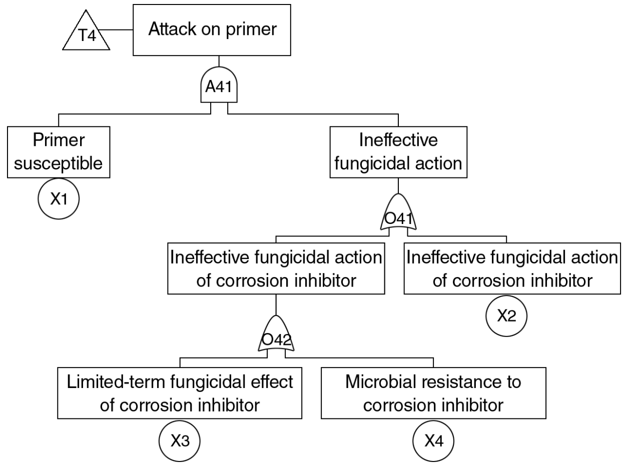


**FIGURE 9.** *Sub-tree T4: fungal attack on primer coat.*

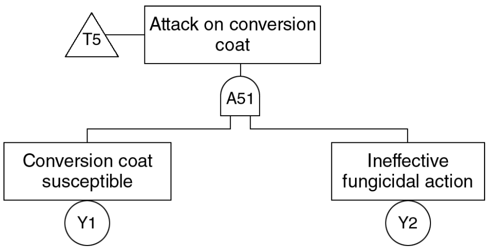


**FIGURE 10.** *Sub-tree T5: fungal attack on substrate.*

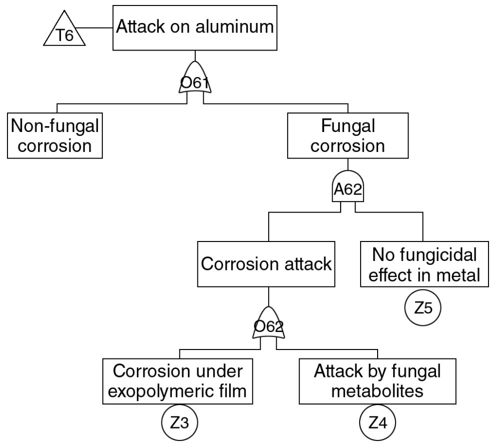


**FIGURE 11.** *Sub-tree T6: fungal attack on substrate.*

processes, the presence of a fungal film on the bare metal, susceptibility to fungal attack, and absence of fungicidal action in the metal are the necessary conditions. A variety of mechanisms for fungal corrosion of aluminum have been proposed in the literature. Fungi may have a direct influence on the kinetics of the anodic or cathodic reactions. Fungal films on the bare metal surface may form microenvironments and establish concentration cells based on oxygen, protons, or metal ions, thereby promoting corrosion. Organic acid metabolites produced from fungi may directly corrode the metal, and the formation of exopolymeric materials by the fungi may alter the characteristics of the native oxide film.

## *Minimum Cuts Set Analysis and Mitigation Actions*

A minimal cut set analysis was performed on sub-tree T1 using the equivalent block diagram approach as shown in Figure 12. T1 has four minimal cut sets and can be represented by the following Boolean expression:

T1= [V1.V2.V3.V5.V6] + [V1.V2.V4.V5.V6] +
[V1.V2.V3.V5.V7] + [V1.V2.V4.V5.V7]

These cut sets represent the four alternate sets of circumstances or pathways leading to the presence

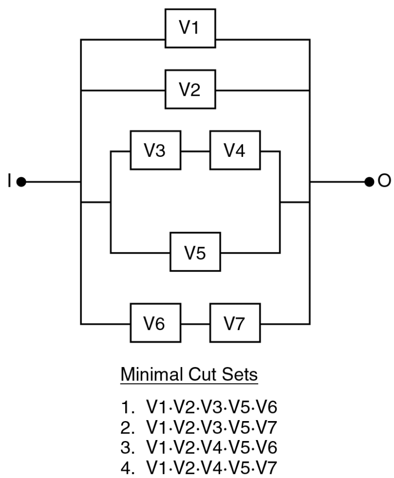


**FIGURE 12.** *Minimal cut set analysis for sub-tree T1 (Figure 6) using the equivalent logic-block diagram method. The AND gate is represented by a parallel pathway and the OR gate by a series pathway. Minimal cut sets are the smallest combination of blocks that interrupt all possible connections between the input and output points.*

**TABLE 2**

*Mitigation Matrix for Basic Factors in Sub-Tree T1 (Figure 6)*

| Basic Factor | Maintenance | Design | Coating Development | Testing | Research |
|---|---|---|---|---|---|
| V1[A] Ineffective cleaning | Optimization of field/depot inspection and cleaning schedules; use of authorized cleaning solutions and procedures | Better access for inspection and cleaning (e.g., in bilge areas, behind equipment and avionics racks, overhead and under-floor compartments, etc.) | Coating finishes that inhibit fungal colonization | Evaluation of new and more effective cleaning solutions and treatments that completely eliminate hyphae from surfaces | Fundamental factors influencing anchoring of fungal biofilm on coated surfaces<br>Technology – automated cleaning tools |
| V2[A] Fungal spores present | Cleaning of air intake ducts | Sealing of occluded spaces; improved environmental control systems and high-efficiency particulate air (HEPA) filtration | | Rapid detection methods | Identification of active genera that cause coating degradation and corrosion of Al |
| V3 Sufficient relative humidity | Attention to high-humidity spaces; storage of aircraft in controlled humidity enclosures | Modular dehumidification systems for aircraft | Enhanced hydrophobicity | Moisture/relative humidity sensors, monitoring systems | Desiccation resistance of active fungal genera |
| V4 Other moisture (condensed water, trapped water) | Disinfection/cleaning of bilge and other areas of water accumulation | Hermetic designs; improved water collection and drainage systems | Smart coatings responsive to environmental changes | Retrievable bio-probes for areas of water accumulation | External inhibitor/ fungicidal dosing systems for water entrapment areas |
| V5[A] Thermal conditions | Cleaning of warm, damp spaces at high risk for fungal colonization | Air conditioning; adequate ventilation in heat dissipation areas | | | Optimum temperature ranges for active fungal genera |
| V6 External sources of fungal nutrition | Removal of dust, planktonic matter, and organic residues such as oil, fuel, grease, etc., from coated surfaces | Minimize potential for contact of coated surfaces with organic materials such as polymers, fabrics, lubricants, etc. | | Fungicides for grease, lubricants, lanolin, etc. | Mechanisms for scouting and assimilation of external organic matter by fungi |
| V7 Coating itself as source of fungal nutrition | Refurbishment of damaged coatings | Select coatings resistant to fungal degradation in the design stage | Resins and additives more resistant to enzymatic breakdown | Evaluation methods for efficacy of new fungistats /biocidal coating additives; fungicidal effect of non-chromate corrosion inhibitors | Factors determining coating susceptibility to fungal attack; fungal attack mechanisms on coating layers and constituents |

[A] Recurrent factor in all minimal cut sets.

of a fungal biofilm on the surface. All the minimal cut sets for sub-tree T1 are of the 5th order and, in the absence of any quantitative information, may be considered to have equal importance ranking.

To reduce the overall likelihood of the presence of a fungal film on the surface, each of the four minimal cut sets, representing a unique failure pathway or system vulnerability, should be mitigated. Mitigation actions can be designed to target all the specific factors involved in the individual minimal cut sets. Closer examination shows that the factors V1 (improper cleaning and maintenance), V2 (presence of fungal spores), and V5 (conducive thermal conditions) are common to all minimal cut sets; therefore, mitigating these factors would achieve the greatest impact.

Table 2 shows a mitigation matrix of possible actions for all the basic factors. For each basic factor

(V1 through V7), mitigation actions are presented. The possible mitigation actions have been classified into five categories: maintenance, design, coating development, testing, and research. Each cell of the matrix may be populated with additional actions as further analysis or additional information is available. To illustrate the use of the mitigation matrix, two basic factors, V1 and V7, are considered:

Mitigation actions for basic factor V1—ineffective cleaning:

—Maintenance: optimize field/depot inspection and cleaning
—Design: better access for inspection and cleaning
—Coating development: coating finishes that inhibit fungal colonization
—Testing: evaluation procedures to rank effectiveness of cleaning solutions
—Research: enhance understanding of fundamental factors that control anchoring of fungal biofilms
—Research: development of more effective, automated cleaning tools

Mitigation actions for basic factor V7—coating itself is a source of nutrient:

—Maintenance: refurbish damaged coatings
—Design: select coatings that are resistant to fungal degradation in the design stage
—Coating development: develop resins and additives more resistant to enzymatic breakdown
—Testing: evaluation methods for effectiveness of fungistats/biocidal coating additives
—Research: enhance understanding of factors determining coating susceptibilities and fundamental fungal attack mechanisms

So, the use of the mitigation matrix can provide a rationale for mitigation strategies in each of the categories.

A similar minimal cut set analysis and mitigation matrix can be developed from each of the sub-trees T3 through T6 as detailed information on basic factors becomes available. It should be noted that since the minimal cuts sets for each sub-tree are also parts of the minimal cuts sets for the main fault tree T, any mitigation actions proposed for each sub-tree will also reduce the overall likelihood of occurrence of the adverse top event of the main tree.

## THREE APPLICATIONS OF FAULT TREE ANALYSIS

Setting up the fungal-induced corrosion problem in a FTA framework provides the means for a systematic analysis of the factors involved and guides their mitigation. In the interest of demonstrating useful applications of FTA, illustrations are presented for corrosion mitigation, design and materials selection, and failure analysis.

### *Fault Tree Analysis Application to Corrosion Mitigation*

The presence of a fungal biofilm/spores on the coating or metal surface is a basic requirement for fungal-induced damage, and control of this provides a tactic for effective mitigation of fungal degradation. The use of FTA is described to identify actions and approaches for corrosion mitigation (Table 2 and Figure 6). The top adverse event for sub-tree T1 is the formation of viable fungal biofilm on the surface. Biotic viability and ineffective cleaning/maintenance are required. Here, the focus is on cleaning and maintenance.

Rows V1 and V2 in Table 2 identify a number of pertinent factors regarding maintenance, design, coating development, testing, and research. Maintenance and testing focus on current procedures and implementation: efficacy of the cleaning solutions, cleaning procedures/protocols, and inspection/monitoring. Design and coating development provide technological advances: better access, self-healing coatings, improved cleaning agents, and automated cleaning tools. Research opportunities include determination of fundamental factors that influence anchoring of fungal biofilm on coated surfaces. Surface energy of the coating substratum is an important factor that dictates the presence of fungal biofilms/spores and ability to bind to the coating surface. Increased understanding would guide development of cleaning agents and procedures and development of self-healing coatings.

### *Fault Tree Analysis Application to Design and Materials Selection*

The design of a multi-layer coating system on aluminum and the "fungal-relevant" properties of each layer will determine the level of susceptibility or magnitude of the risk of fungal-induced corrosion. For an intact and undamaged coating system, Figure 7 and Table 1 depict the sequential attack of layers necessary for exposure of the aluminum substrate. The fault tree for each layer is depicted as a simple combination of the susceptibility of the layer to fungal attack and the ineffectiveness (or lack) of fungicidal action. Typically, the primary barriers to coating degradation and corrosion reside in the primer and conversion coat layers. Biocides with fungicidal action and corrosion inhibitors protect the coating layers and aluminum substrate, respectively. Ineffective fungicidal action from the primer or conversion coat provides failure paths as shown in Figures 9 and 10. Alternatively, the benefits to corrosion mitigation from effective fungicidal action and corrosion inhibition in these two layers are clear.

FTA provides a systematic means to track and communicate the benefits of effective fungicidal action in coatings. Chromates have both fungicidal and corrosion inhibition behaviors, and effective primers and conversion coatings with chromates have been widely used. So, the restrictions and prohibitions on use of chromates and requirements have a significant impact on corrosion mitigation strategies. The search for and validation of corrosion inhibitors in primers that have effective biocidal properties comparable to chromates is an area of active research.

### *Fault Tree Analysis Application to Failure Analysis*

FTA provides a useful tool for failure analysis of corrosion of coated aluminum. Table 1 shows the pathways for aluminum substrate corrosion to occur. Corrosion of the underlying aluminum alloy occurs only after each coating layer is breached via fungal or mechanical action. Figure 7 presents the sub-tree for fungal attack of exposed aluminum substrate. On the right branch for fungal corrosion, for fungal-induced corrosion to occur, there must be no effective fungicidal action from the metal itself, i.e., a biofilm can form. In addition, the corrosion must be fungal-induced. This could result from the exopolymeric film on the aluminum or from fungal metabolites resulting in a corrosive environment.

A fundamental concern is whether the fungi do indeed influence the corrosion. This question is obvious but not necessarily straightforward to discern. Fungi may be present; however, they may not be a causative agent either through direct action or enzymatic effects on the environment. As with development of non-Cr coatings, this discernment of fungal-induced action is an area of active research.

## CONCLUSIONS

❖ FTA provides a structured framework for analysis of corrosion problems through a detailed examination of causal factors and their inter-relationships. The use of FTA methodology was demonstrated for qualitatively analyzing the combinations of factors that could result in fungal-induced degradation and corrosion of coated aluminum in aircraft. The interaction between fungal-induced degradation processes and coatings were described, and the methodology of FTA was presented. The objective was to demonstrate the identification of failure pathways and mitigation actions for reducing the risk of fungal-induced corrosion of coated aluminum in aircraft.

❖ Using information available in the literature, the FTA methodology was applied to set up a basic fault tree considering general factors involved in the formation of a viable fungal biofilm on the surface, sequential fungal attack on individual layers of the coating stack-up, and the fungal-mediated corrosion of the substrate metal. A qualitative analysis of the minimal cut sets of the fault tree revealed pathways and vulnerabilities that can form the basis for developing interceding actions and mitigation strategies.

❖ Minimal cut set analysis performed on the sub-tree for fungal-film formation revealed four critical pathways, with three factors common to each, viz., improper cleaning and maintenance, presence of fungal spores, and conducive thermal conditions. Possible mitigation actions were proposed in the form of a mitigation matrix to reduce the occurrence of a fungal film and, consequently, the overall likelihood of fungal-induced corrosion. The possible mitigation actions were classified into five categories: maintenance, design, coating development, testing, and research. To demonstrate useful applications of FTA, illustrations were presented for corrosion mitigation, design and materials selection, and failure analysis.

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