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Forensic Engineering: Part A

Conducting Failure Analyses of Metallic Materials

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Introduction –

This is Part A. of a two-part course on forensic engineering that considers the analysis of metallic material failures. Part A. presents an introduction to forensic engineering and the process of completing root-cause failure analyses (RCFA). The typical steps in carrying out a failure analysis and some of the pitfalls to avoid are discussed. Common, generic causes of failures are reviewed along with metallic material characterization techniques that are typically used in RCFA. Part B. discusses, in detail, several of the important mechanisms of metal failure and provides alternative control methods for each that may be used to prevent a reoccurrence.

Forensic engineering and the task of completing root-cause failure analyses (RCFA) can cover many activities. In all cases the goal is to determine why a system or component failed to achieve its intended function or life. Professional engineers that do forensic work and failure analysis typically concentrate in one of the many technical areas.

Failure analysis in the metallurgical engineering field is a major activity in forensic work and that is the subject of this course. In metallurgical failure analysis the focus is on the material and design of the part or component at the point or origin of the failure in the overall system. Many classes of engineering materials are used including metals, polymers, ceramics and composites. In general, metals are the most common category used. Carbon steels, stainless steels and cast irons are encountered most frequently but, depending on the application, the other common metallic materials used are aluminum, copper, nickel and titanium alloys.

There are two distinct uses of RCFA and forensic engineering. One occurs in commercial or industrial settings and the other applies in litigation cases. Typically the industrial failure analyst has the goals of defining the specific cause (or causes) of a failure and then, of equal or greater importance, he or she must make practical recommendations to minimize the possibility of a reoccurrence. Often this analysis is vital to the industrial concern for personnel safety or economic operation reasons. In these circumstances one of the worst things the operational manager can do is make like-for-like replacements of failed components without reaching a conclusion about the basic cause. Only then should indicated improvements be implemented.

In litigation cases, an attorney will retain the failure analyst/expert witness to assist him or her to determine the physical cause of a failure. The essential use for that information is to provide evidence to allow liability to be assigned. The attorney's objective is to either gain a monetary settlement or judgment for his client or to show that his client is not liable for the failure – depending on whom he is representing. These legal cases usually involve civil (versus criminal) law and typically are either product liability or personal injury actions. Here the forensic engineer's formal job function per Reference 1 and as written in the Federal Rules of Evidence 702 is to use "scientific, technical or other specialized knowledge" to assist the trier of fact to "understand the evidence or to determine a fact in issue". The trier of fact is either the jury in a jury trial or the judge in a bench trial (without a jury). The rationale is that the trier of fact may not be able to fairly access the specialized factors in a given case without assistance from an expert such as a forensic engineer.

This course concentrates on the physical causes of metallic failures. However, frequently there are latent causes that are at least contributory if not primary in the physical failures. These are actions and inactions due to decisions by individuals and particularly those in leadership positions that indirectly caused the physical failure. For example, inadequate maintenance may have produced the failure and that deficiency was in turn caused by too many assigned tasks for the available maintenance staff or because of poorly trained maintenance personnel. Someone in management likely decided the number of maintenance people needed and what training they should have. Often those decisions were dictated by economics –and maybe they were justified on that basis – but they also could have been the background causes that lead to the physical failure. Clearly these issues are seldom clear-cut and more importantly they are often politically sensitive. Latent causes are not discussed here but the reader is referred to Reference 2 as a good source of additional information about this important but difficult topic.

Generic Reasons for Service Failures of Metallic Materials –

Several mechanisms produce metallic failures and these are discussed in detail in Part B. of this course. First it's useful to note some of the general, classes of problems that often lead to specific failure mechanisms. The overall problem areas, in no particular order of importance, are as follows:

- Incorrect material selections,
- Material defects due to processing or fabrication,
- Design defects,
- Unexpected service conditions and
- Intentional or unthinking abuse or misuse.

Table 1 provides some specific examples in each area and the resulting failure mechanisms that often are the results. An initial step in a RCFA should be to consider these general causes of problems in view of the circumstances of the given failure. Doing this allows the analyst to start forming some first questions to ask or investigate before he or she narrows the discovery process to checking specific failure mechanisms. But – don't be mislead or jump to conclusions too early in the analysis because it appears the root cause of the failure is "obvious".

The word “defect” should be used very carefully especially in legal cases. Most all materials have imperfections or flaws. However, unless one of these characteristics directly contributes to the specific failure mechanism at issue it should not be considered a defect. In the legal area, this word implies a definite role in a given failure and, therefore, should be reserved for that usage alone.

Table 1. – Generic Classes of Metallic Failures, Examples and Common Results

Incorrect material selection & use	
Use of a soft metal, e.g., aluminum or copper in a wear application	Accelerated wear
Use of brass in an ammonia environment	Stress-corrosion cracking (SCC)
Use of a low-toughness alloy at very low temperatures	Brittle fracture
Material defects	
Improper heat treatment	Incorrect strength or ductility
Out of spec chemical composition	Accelerated corrosion or poor mechanical properties
Lack of complete fusion in welds	Reduced strength; stress-concentration is created
Design defects	
Failure to specify a requirement to remove machining marks on a rotating shaft	Shortened fatigue life
Copper & steel in electrical contact in the presence of a corrosive liquid	Galvanic corrosion of the steel
Improper casting mold design	Incorrect shape or sectional thickness

Table 1. –(continued)

Unexpected service conditions	
Abnormal, severe conditions during start-up or shutdown of a manufacturing process	Failure mechanisms not seen at normal operating conditions
Micro-motion between bearings and bearing races is created during storage & transit	Fretting wear
Abuse or unthinking use	
Operating an ASME code-built pressure vessel above its design pressure or temperature	Static stress overload and, possibly, fracture
Homeowner using a large wrench or a large screwdriver as a prying bar	Injury to the homeowner, or the tool or both

Steps in a Root-Cause Failure Analysis –

The scientific method provides a guideline for completing a root-cause failure analysis (RCFA). The method requires defining the question to be answered, proposing alternative hypotheses, testing or evaluating each hypothesis and, finally, drawing a conclusion as to which alternative is most viable. In the case of a RCFA the analogous steps are answering the overall question of why the failure occurred by using the sequential steps of proposing possible alternative failure mechanisms, devising and completing relevant evaluation or test procedures for those alternatives and, from the results, coming to conclusions as to which alternative was the root cause and, possibly, defining contributory causes.

The failure analyst has to apply good judgment and, often, diplomacy and skilled communication in defining and explaining the appropriate depth of his or her analysis in each specific case. The consequences and/or economic value of the loss from the failure incident should determine the degree of thoroughness (and therefore cost) that is justified for the given situation. Often the client will push for a quick and, therefore, inexpensive analysis and answer. In a few situations that is all that is needed but more commonly a complete analysis is required when the problem is not so clear-cut and/or the results of a cursory investigation could have much worse consequences later. Determining the correct level of effort in a given situation and, when needed, effectively communicating the rationale for a costly analysis to a reluctant client are important skills for the failure analyst. The same skills are also needed in recommending and defending suitable control measures to prevent a reoccurrence of the failure. The effective analyst should realize the importance of these, so called, soft skills. Technical expertise is a necessary but far from sufficient characteristic of the successful failure analyst.

A failure analyst's tasks and emphasis in legal versus non-legal work has some important differences. In a RCFA performed in a legal case the steps involving recommendations to mitigate a reoccurrence of the failure are usually not required. However, additional work in preparing and presenting the evidence is required that is usually not needed in industrial applications. The engineering expert witness will need to write his or her report in a manner so that the information is easily understood by persons without technical training. This also applies even more so to evidence to be presented at trial. Use of appropriate but simple analogies that convey a clear message are particularly useful and a good picture is often worth many words. In a non-legal setting this degree of preparation and explanation is not usually needed because at least some of the people that will review the analyst's report and recommendations will have technical backgrounds.

There is another important function that the forensic engineer may be able to provide in a legal case. It may be that the analyst will find that the results of his or her analysis are not going to be favorable to the case that his retaining attorney is seeking to prove. In this situation the analyst - as a licensed professional engineer – is ethically bound to truthfully inform the attorney and explain his results and the technical deficiencies in the case. Hopefully, this result will occur before the attorney has officially identified, i.e., designated - is the tem used, the analyst as an expert witness for his case and before that analyst's findings have been disclosed in a report to the opposing counsel. A designated expert will be legally sworn to tell the truth. He will be subject to intense questioning in his deposition and through cross-examination by the opposing attorney at trial. If the engineer's findings are unfavorable to his retaining attorney's legal claim, the attorney may decide to settle the case or to go forward with the case but not designate the engineer as his expert. Often the engineer will be dropped at this point. However, sometimes the attorney can greatly benefit by continuing with the case but with the forensic engineer in an undesignated, consulting role.

As an undesignated, consulting engineer in a legal case all communications between lawyer and engineer are privileged and thus protected from disclosure to the opposing counsel. The undesignated forensic engineer is free to assist the retaining attorney by suggesting an alternative technical approach to proving his case (maybe by suggesting the use of an expert in another science or engineering specialty), by suggesting questions for the attorney to ask the opposing expert in deposition or at trial to discredit him or by giving input on how complex engineering evidence should most effectively be presented at trial. In a given case, "The glass is half full."

and "The glass is half empty." may both be true statements. The engineer often can make useful suggestions to the attorney to allow him to present his case in the best light possible.

As stated earlier, a very detailed and thorough RCFA process is not justified for investigating all failures. The analyst learns through experience what level of effort is reasonable and needed for different applications. Following are the commonly used sequential steps in completing a thorough RCFA when substantial depth of evaluation is required:

Gather background facts and physical evidence -

The analyst needs first to get all possible information related to the failure as soon after the incident occurs as possible. The best situation is to visit the failure site to accomplish this and do a thorough personal inspection including speaking immediately with individuals that were there at the time of the failure and/or had personal knowledge of what occurred and that can supply other relevant facts. The much less desirable, alternative is to speak with the most knowledgeable individuals as soon as possible but not personally visit the site initially. The importance of obtaining and protecting the physical evidence, e.g., fractured or worn components from the failure, needs to be clearly conveyed to those on the scene if the analyst does not visit the site immediately.

Typically it is very useful (or vital) to get on-site photographs of the failure scene and surrounding items before anything is disturbed. If the failed component has already been moved it may still be useful to photograph the area of the failure so as to document the original location relative to other items. The photographs should be planned to clearly show first the overall context in which the failure occurred and then the detailed aspects of the damage on the part in question. It is generally good practice to include something of known size, e.g., a ruler, a coin, a standing person, etc., in photographs to indicate relative sizes for later, comparative reference. Adding small signs or other makers to the photographed scenes or areas to indicate, for example, flow directions, top or bottom of the pipe or location of a nearby component not in a photo can be very useful. Always take more photos than you think you need. Later examination of the printed photos often reveals important features of the failure or the site that you had not initially recognized.

The interview (or interviews) of the most knowledgeable person (or persons) at the failure site is a vital part of the RCFA. If several people will be questioned it's important, if at all possible, to conduct a separate interview with each person. This allows each individual to speak freely and not be constrained by others present. If conflicting information is given, the analyst can resolve the issues by asking additional questions later. Opinions about the root-cause of the failure may be interesting to note but it at this point it is premature to give them much value.

Following are specific guidelines on what information to seek and how to conduct effective interviews during this phase of the analysis:

If it is not initially clear, the analyst should ask enough questions an/or seek appropriate documents so that he or she is completely sure of the specific operation and function of the failed component and how it fits into the overall purpose of the equipment or system.

Determine when the failure occurred, how long had the component been in service before this failure and whether or not a similar failure had occurred previously. If a prior failure had occurred determine how long was that component in service before the failure.

Determine the normal service conditions that the current failed component was exposed to during regular operations, e.g., temperature, pressure or other stresses, flow velocity, rotational speeds, chemistry of the corrosive medium exposed to the part, details of the lubrication system/method used (if applicable), etc.

Determine (to the extent possible) if the failed component was ever exposed to other more severe conditions for short periods such as during start-up, shutdown or due to temporary conditions upstream in the flow system. Determine specifically what these conditions can be. Define what occurs when these upset or temporary conditions apply.

Determine the service conditions – normal and temporary – when the previous failure(s) occurred.

Determine the design, operating and maintenance specifications or procedures that applied when this failure occurred. Examples of design specs might include the dimensions and tolerances of the failed part; the particular material, composition and heat treatment specified; the manufacturing or fabrication processes used (e.g., machining, casting, forging, welding or if mechanical fasteners were used) or the coating or surface case hardening specified. Much of the design information will be included on drawings, in spec books or on purchase orders. Some will have to be obtained from vendors. Operating and maintenance procedures may be documented but should be confirmed and fleshed-out via interviews.

Determine if the same design, operating and maintenance factors applied when the previous failure(s) occurred. If not – determine the specific differences.

If available, obtain copies of relevant documents that were intended to define specific design features of the failed component plus the operating and maintenance procedures that supposedly were used. These should be reviewed later and compared to information obtained in the interview(s).

Obtain complete details on all manufacturers or vendors that had a role in supplying or fabricating any of the materials or equipment involved in the failure. Get information on suppliers' names and locations plus model and serial numbers, design conditions, etc. from equipment nameplates whenever possible.

Guidelines for the personal interviews: Ask broad, open-ended questions and let the person being questioned talk freely and volunteer as much information and personal insight as possible. LISTEN much and speak little. Ask for details to support any opinions that the person being questioned expresses. Present yourself as an outsider that has much to learn about the specifics of the conditions and circumstances around this failure. Say and show that you are grateful for any help the person being questioned can offer. Never be judgmental or show a lack of respect for anyone! Be very hesitant to express your initial opinions before all the facts can be assembled and analyzed. Don't make premature promises regarding completion of your work. Obtain complete contact information for each person interviewed for later, possible follow-up questions.

Keep clear and complete notes based on measurements, observations, impressions, etc. from the visual inspection and from information gained in the interview(s). Potentially important, facts may fade from memory – maybe weeks later - when subsequent steps are completed.

It is essential to carefully obtain and preserve all the physical evidence involved in the failure. If possible remove the failed component from the overall equipment or structure being very careful not to alter or damage the fracture surfaces or adjacent areas of the metal. Torch cutting and rough abrasive cutting nearby the fracture surfaces especially should be avoided because metallurgical features (that may be essential in the subsequent analysis) can be altered by the heat generated. Never attempt to touch or "clean off" any deposits on fracture surfaces or nearby areas or to "fit together" fractured parts. Valuable evidence can be destroyed by these unthinking actions. Touching fracture surfaces can alter them by leaving perspiration, i.e., corrosive chloride ions, or oils from your fingers on the surfaces. The analyst may see loose particles on the as-found surfaces that can be important in identifying the failure mechanism. These may adhere to fingers that touch the surfaces. Protect the fracture surfaces during transport from subsequent damage due to physical contact with each other, other metals and materials or corrosion by separating and protecting them with a soft, clean cloth (such as cotton). If possible, put the entire component inside a clean, sealed plastic bag to minimize the entry of air and moisture.

Physical evidence may also include obtaining samples of the process liquid that was exposed to the failed part when corrosion is implicated. This is true unless the specific chemistry of this liquid is very well known. If this is not true then defining such parameters as the specific pH of the liquid, the concentration of aggressive species and ions or the presence and concentration of the specified corrosion inhibitor may be critical to the RCFA. Store and safely transport the process liquid for later pH measurement in a glass and not plastic container. Air can diffuse through certain plastics and this could alter the original pH of the liquid inside. Obtaining lubricant samples from the area of a failure that appears to be induced by wear often can provide valuable information after specialized analysis. Don't alter the as-found lubricant in any way before putting it in a completely clean and secure container for transport to a laboratory for analysis.

Obtain an exemplar if at all possible. This is an intact part or component identical or similar to the failed item. Ideally the exemplar will have been exposed to similar service conditions and has been installed for a similar period as the failed item. Photograph the exemplar in-place if possible before removing it. Later comparisons between characteristics of the exemplar and the failed part(s) may provide very useful information pointing to the cause(s) of the failure. Record any differences that are initially known between the failed part and the exemplar.

Complete a thorough visual exam of all physical evidence–

Generally the more detailed, non-destructive examination of the evidence can be done more effectively and thoroughly in an office or lab rather than in the field. Use of a small magnifying glass or, alternatively, a light microscope examination of the unaltered evidence in a lab can provide much useful information before going to more costly procedures. For example, the initial indicated mechanism of failure, e.g., ductile versus brittle fracture, static stress overload versus fatigue failure or corrosion versus wear frequently can be estimated by this simple visual examination. In addition the types of further analyses that will be needed can be estimated. If needed laboratory tests or procedures that require destruction or alteration of the evidence are recognized then the locations of appropriate cutting planes can be estimated during this initial exam.

Estimate the most probable alternative causes of the failure–

Correlate the information gained in the visual examination with all information and facts obtained in the field and interviews to define two or three of the likely failure mechanisms. Some evidence from the visual exam and interviews will typically be in conflict with the intended characteristics defined by specifications, normal service conditions, mode of operation, maintenance accomplished, etc. These conflicts may lead to different failure causes not initially defined and the types of analyses that will be needed to reveal the truth.

Devise and complete the indicated analysis plan –

It is essential that the analyst thoroughly thinks through and creates a detailed plan for doing the kinds, and sequence, of analyses that will be needed to support or refute the likely alternative failure mechanisms. Depending on the specific case, the plan might start with gathering more detailed information from the client or manufacturer, doing basic stress calculations or completing other simple estimates. A need may be identified to do more complex calculations, e.g., completing a finite-element stress analysis or using other software to assess fluid flow or heat transfer factors. Always begin with the least complex and inexpensive task and, if needed, go to the next level of complexity and cost. If indicated the next logical steps may be destructive laboratory examinations or tests to characterize the failed material. Here too in terms of the work that will alter or destroy evidence, the task progression should always be from the least to the most destructive of the available evidence.

Table 2. provides a summary of commonly used laboratory procedures and the kind of information each typically produces. Standardized test and analysis methods, e.g., as defined in ASTM standards, should be used wherever possible. Many types of analyses can be done. Only the frequently used ones are cited in Table 2.

<u>Table 2. – Common Metallic Material Characterization Techniques and Their uses</u>

Visual inspection and photographs of the failure scene and component.	Provides an overall assessment of the failure and establishes a basis for needed work.
Light microscope and/or scanning electron microscope (SEM) examination of the failed component (before any destructive alteration).	Initial indication of the likely failure mechanism and contributing factors. If the fracture surfaces are readily available the SEM exam can provide valuable information at this time. However, this may have to be delayed until the as-found item is altered later.

Table 2. – (continued)

Energy-dispersive spectroscopy (EDS) as part of the SEM exam of the fracture surfaces.	Provides semi-quantitative identification of most chemical elements present on the fracture surfaces. This data can indicate the primary failure mechanism or contributing factors.
Alloy hardness measurements on the failed component and exemplar.	Defines relative strength and resistance to wear. Provides general indications of the heat treatment processes used.
Metallography (a destructive technique)	Much important information can be gained. For example, before etching, a prepared metallographic section can show the morphology of the failure and adjacent unaffected areas. After etching the prepared section can show the microstructure of the the alloy, the metallurgical phases present, the sizes of grains, whether cracking was intergranular or transgranular and the thickness of surface case hardening.
Optical emission spectroscopy (OES), inductively coupled spectrometer (ICP) or atomic absorption (AA) [each is a destructive technique]	Each method provides accurate values of the percentages of various chemical elements contained in an alloyed metal. The specific composition of an alloy can be important to the failure in several ways. OES costs less to complete than either ICP or AA but it requires a greater quantity of metal to complete the analysis.
X-ray diffracion (XRD)	Can serve several purposes. It can be used to define the identities of chemical compounds (and not just elements), define the level of residual stress present in a cold worked alloy and assess the wear particles found in a used lubricant after an adhesive wear failure.

Initial macro-scale photographs of the failed part plus photos of micro-scale features on it that are seen during the light microscope and/or scanning electron microscope (SEM) examinations are typically made to document results. The same is true of microstructural features observed on prepared metallographic specimens taken from the failed part. Standard mechanical property tests of the material, e.g., to establish yield and tensile strengths, degree of elongation or fracture toughness, may be indicated if sufficient material to make test coupons is available. ASTM test methods are generally used for any mechanical property testing with coupons.

Frequently some of the same types of analyses completed for the failed part are also done using an exemplar. The comparative data generated can provide valuable immediate information and sometimes it can indicate new areas that need to be investigated.

In legal cases a test and analysis protocol typically will have to be written, reviewed and approved by all parties in the suit before any activity that requires even partial destruction of physical evidence is started. Otherwise opposing counsel can make accusations of spoliation of evidence and then the court could throw out the case. Even in RCFA's that do not involve litigation it's important to develop a rational and detailed plan for the overall analysis sequence so that no evidence is destroyed prematurely.

Make conclusions based on all information obtained –

Generally, a definitive, "smoking gun" type of result will eventually come out of the overall investigation. This will indicate which of the original possible causes is best supported by the *all the facts* gathered and which one (or ones) is not. Consistency is the key. If all the findings agree in support of one of the hypothesized failure mechanisms the answer to the puzzle is clear. However, if this is not true rethink the estimated failure process to determine possible alternatives and the analyses that will be necessary to prove or refute them. The analyst has to keep an open mind to the possibilities that were not originally considered. Sometimes critical evidence will be destroyed before the analyst has an opportunity to evaluate it and, unfortunately, a definitive root-cause may remain unclear. Even so, much may have been learned by the process to prevent a similar reoccurrence.

It is human nature to think and look where we are most comfortable and form opinions based on our personal experience and biases. Because of this reality the most effective analyst will be aware of a range of possible effects and of his own limitations. Often a team of individuals with diverse technical backgrounds is justified on complicated failure analyses. Even in less difficult cases it is useful to have a competent person with a different technical expertise review and critique your work. This is to make sure that a key factor from the second party's perspective has not been overlooked. It is said that a man with a hammer only looks for nails to drive. Be aware of the potentially significant value of other viewpoints and experience that is different from your own.

Define alternative corrective actions –

In an industrial or commercial application, it is essential for the failure analyst to recommend effective corrective actions to prevent or control a repeat of a failure after the root cause (or causes) has been established. Here the analyst should consider all possibilities that might be useful for the specific failure mechanism and application realities. Depending on the particular situation there may be a short or a long list of possibilities.

Part B. of this course discusses the details of the most common metallic materials failure mechanisms. This knowledge provides a general foundation for establishing and understanding the rationale for many of the control or corrective actions that can be useful for specific types of failures. However, while specific explanations are not given here, the corrective actions provided in Table 3 illustrate some of the common approaches that might be helpful to prevent a reoccurrence of failure in the given application. These actions are not presented in any order of effectiveness or desirability. Every situation is unique and different practical restraints on what can be used always exist.

Table 3. – Examples of Possible Actions to Correct or Control Metal Failures

Modify the design details, e.g., minimize stress concentration points; provide for complete drainage of process liquids; eliminate all possible residual stresses in the material; eliminate all possible crevices or other details that could concentrate aggressive corrosive ions; specify a case hardening or a higher quality finish for the metal surface.

Modify processing and/or fabrication methods, e.g., heat treatment processes; welding processes; machining, casting or forging processes; use welds instead of mechanical fasteners.

Change the material to obtain needed properties, e.g., higher strength; better ductility; greater fracture toughness; greater corrosion resistance; greater fatigue strength or wear resistance. Consider less traditional alternatives, e.g., a thin layer of a stainless steel for corrosion resistance metallurgically bonded to a thicker carbon steel plate to provide strength or use a polymeric material or a composite material instead of a metal alloy if the required criteria for the application (for example, strength or other mechanical properties, temperature resistance,

Table 3. (continued)

thermal conductivity, wear resistance, ability to fabricate or allowable cost) will permit the substitution.

If feasible, change one or more of the operating and environmental service conditions so as to expose the installed alloy to less demanding circumstances. For example, rapid start-ups or shutdowns of operating equipment can present extra requirements for materials to withstand – determine if these procedures can be modified. Determine if normal operating conditions that directly affect metal performance can be altered to less severe levels, e.g., by lowering temperatures, pressures, rotational speeds or fluid flow velocities; by installing strainers in flow streams to remove large, hard solid particles or by carefully controlling the chemistry of process liquids in terms of pH and the concentration of aggressive ions present.

Consider the use of a damage-tolerant design and maintenance approach. This involves the acceptance of growing cracks or defects in alloys of known fracture toughness coupled with determination of the critical size of those defects by fracture mechanics principles and a program of regular monitoring using non-destructive evaluation (NDE) techniques. If such a program already is being used determine if it is being conducted properly.

Determine if the added costs of more frequent or more thorough maintenance procedures or more failure resistant materials can be economically justified compared to the overall cost of unplanned shutdowns of the equipment or system.

Change or modify the corrosion control method(s) being used. The major classes of control are coatings, material selection, cathodic protection and the use of chemical inhibitors. Determine if the most effective method is being employed.

If adhesive wear is identified as the failure mechanism, closely evaluate the type of lubricant being employed and the system used to deliver it.

If material or fabrication defects have been established as the source of failures, consider modifying purchasing specifications, increasing NDE completed or changing suppliers.

Sometimes the best approach may be to redesign the equipment or system to allow for relatively easy accessibility to failure-prone components, regularly monitor their condition and make replacements as needed before an unsafe condition develops.

Determine the practicality of the various corrective actions and choose the best –

The analyst is likely to be the best judge of what technical actions can most effectively prevent a reoccurrence of the particular failure. However, the client is best qualified to judge which of the alternatives is going to gain acceptance in his or her organization. Thus the analyst needs to closely communicate with and obtain needed input from the client. Economics will always be a factor. Completing lifecycle cost analyses – using discounting factors and the techniques from engineering economics - often can provide a solid basis for rational decision-making. Sometimes the results of a valid lifecycle cost analysis can convince the client's management that the option with a higher initial cost but better long-term reliability and thus lower overall cost is a better choice. Sometimes, however, rationality is overruled by other factors beyond the control of either the failure analyst or the client's representative with which the analyst interacts.

The best solution and recommendation is of no value if the client will not or cannot implement it. It's much better to actually get an alternative installed and used that is at least an improvement over past practices rather than recommending the ultimate technical solution (in the eyes of the analyst) and have nothing done. As always, honest two-way communication is the key to practical success.

Write the report –

The report should be clear and concise about the results of the RCFA, the recommended corrective action (or actions) and the justifications for those recommendations. It should indicate that a thorough analysis was completed (appropriate to the given situation) and it should provide logical recommendations that will be both effective and practical. While engineers will likely want to see the details, very often the only parts of the report that industrial managers read are the abstract or executive summary and the conclusions. Make sure these parts are brief but they clearly convey exactly what you intend. This is especially true for reports written by expert witnesses in legal cases. However, all the back-up information must be readily available.

Follow-up with the client –

In an industrial application, this last step entails close coordination with the client so as to best implement the recommendations for corrective actions. Continuing the frequent and honest two-way communications that were followed throughout the RCFA sequence is the best way to achieve this.

For RCFA's applied in legal cases, the failure analyst who has been designated by his retaining attorney as his or her expert witness will submit his report that will be closely reviewed by opposing counsel and his expert(s). The opposing attorney will then have the opportunity to aggressively critique the expert and his report in a deposition. The opposing attorney's goals there will be to discredit the expert as well as his findings and conclusions. The designated expert witness has to clearly show during this intense questioning that his technical analysis methods, the conclusions that resulted and the opinions he offered were rational and met an acceptable standard. The standard that is typically applied and expressed by the expert are that his or her opinions are valid within "a reasonable degree of scientific or engineering certainty." In civil law cases, i.e., the typical case where an engineering expert witness will appear, this means that the majority of the evidence (at least with a 51 % probability) supports the opinions given by the expert. Obviously, the expert and his retaining attorney strive to obtain evidence that supports that expert's opinions with considerably more than 51 % probabilities.

The engineering expert witness will again be subject to cross-examination by opposing counsel if the case continues on to a trial. However, while many cases go through the sequence of thorough analysis, expert report preparations, report reviews by both sides and sworn testimony in depositions by experts from both sides - most cases then settle, i.e., the opposing parties come to an agreement because one of the parties will have clearly stronger evidence to support their case. Trials are expensive to all concerned and the party with the weaker evidence takes a chance on having to pay even more if they go to trial and then lose. Only about 10% of civil law cases continue on to the trial stage.

References

1. Federal Rules of Evidence, Article V11, Opinions and Expert Testimony, Rule 702. Testimony by Experts.

2. Web site that reviews the nature and uses of latent (rather than physical) causes of failures: www.failsafe-network.com

3. ASM International, Handbook Vol. 11, Failure Analysis and Prevention, 2002.

