CHAPTER 1

What Is a Failure?

IMPORTANT ASPECTS of failure investigation addressed in this chapter include:

• The complexities of organizing a failure investigation and understanding the importance of defining a clear and concise goal, direction, and plan prior to beginning the investigation
• The many aspects and organizational levels that may contribute to and define a failure
• The role and requirements of leading a successful failure investigation
• The importance of discovering the root cause of a failure through the use of a well-organized and well-planned failure investigation.

Introduction

On January 27, 1967, the crew of Apollo 1 was lost when a fire broke out inside their command capsule during a simulation run aboard a Saturn 1B launch vehicle. This tragic event caused a nation in the midst of the early years of the “space race” to stop, think, and reconsider President John F. Kennedy’s May 25, 1961 promise that “we choose to go to the moon in this decade.” Weeks later, during the federal investigation of the Apollo 1 fire, astronaut Frank Borman proclaimed it a “failure of imagination.” At this early stage of the space program, people simply could not be expected to imagine all the possible problems that could arise.

Two years, five months, and 23 days later, on July 20, 1969, the lunar module Eagle landed on the moon. The command capsule, service module, and lunar module used for that historic space flight and landing had been improved by the rigorous and detailed failure investigation of the capsule from the Apollo 1 fire. A second capsule, the next in line, was also sacrificed in order to better understand the failure and determine its root cause. During the investigation, many other design and manufacturing flaws were discovered, with improvements suggested and implemented.
Failure investigation has come a long way since the Apollo 1 fire. Those involved in failure investigation have an incredible array of sophisticated and powerful tools and equipment to assist them. The world of materials science has evolved in many directions, and extensive research has provided more information on materials than any one person could hope to accumulate in a lifetime.

Unfortunately, many failure investigations performed today are not the victims of a failure of imagination, but rather of a failure of organization. Too many failure investigations are undertaken without a clear and concise goal, direction, or plan. Somewhere along the way, the investigation sputters out of control and never achieves its fundamental purpose: discovering root cause.

Using examples from a variety of industries, this book outlines a proven systematic approach to failure investigation and teaches the steps you need to follow. It discusses the effects of various failure sources, such as corrosion, on the organization of the investigation. It provides a learning platform for personnel from all disciplines: materials, design, manufacturing, quality, and management.

Challenges Faced by Failure Analysts

Increasingly, failure investigation is becoming a public forum. As evidenced by recent television shows, our society is interested in criminal investigations and how the process works. More people now read the results of failure investigations and judge—do not just accept—the final answer. In some cases, the conclusions reached by the failure investigation cannot be derived from the evidence presented. It is mandatory that professional failure investigators be prepared and do the best job possible.

For example, consider the public response to the crash investigation of TWA Flight 800. The aircraft in this July 17, 1996 flight carrying 230 people from New York to Paris exploded shortly after takeoff. The National Transportation Safety Board (NTSB) failure investigation took four years, and it concluded that a stray wire in the center wing fuel tank caused ignition of the flammable fuel/air mixture in the tank. However, eight years after the crash, independent investigations are still ongoing that dispute this conclusion. Some of these investigators contend that a shoulder-fired missile hit the plane and that the government has turned a blind eye to certain facts. Regardless of the credibility of these claims, they indicate that high-profile failure investigations are under increased scrutiny today.

People do not blindly believe what the experts tell them. Failure analysis professionals must understand that their investigations may be received with skepticism, even if all evidence is considered.

But where to begin? Have you ever been handed a failure investigation and felt unsure of all the steps required to complete it? Or perhaps you had to review a failure investigation and wondered if all the aspects had
been properly covered? After reading the results of a failure investigation, do you know what to do next? The initial steps of a failure investigation set the direction and, in many cases, either ensure a successful investigation or doom it to failure. Learning the proper steps for organizing a failure investigation ensures success.

Failure investigation crosses company functional boundaries and is an integral component of any design or manufacturing business operation. However, a poorly organized investigation may not provide the necessary information to solve the manufacturing problem or assist in a redesign.

The Failure Analysis Process

Failure analysis is a process for determining the causes or factors that have led to an undesired loss of functionality. Most failure analyses primarily address failures of components, assemblies, or structures, and the approach is consistent with the knowledge base of a person trained in materials engineering.

Over the past few decades, materials engineers have greatly helped to advance the scientific foundation of failure analysis. Many people still define the causes of failure in a rather binary manner: Was the part defective or was it abused? Obviously, there are many types of defects, including those due to deficient design, poor material, or manufacturing mistakes. Whether such “defects” exist in a given component that is undergoing failure analysis often can be determined only by someone with a materials background—because many defects are visible only with the aid of a microscope. While microscopes may be widely available, the knowledge and experience required to interpret the images is not. Increasingly powerful scanning electron microscopes have helped provide a more fact-based foundation for opinions that may have been heavily speculative in the past.

Design-related defects may require assessment by a materials engineer, as many design engineers are not very familiar with material factors such as the natural variations within a material grade. Every “failed” object is made of some material, and some common materials can lose more than 90% of their usual strength if not processed properly. Clearly, prior to reaching a conclusion as to the most significant causes of the failure, someone must determine whether the correct material was used and whether it was processed properly. This often requires both an investigation of documentation and a series of physical tests.

**Underlying Causes of Failure.** Through work on spectacular failures and on failures that have caused great pain and loss, materials engineers have been led to ask deeper and broader questions about the underlying causes that lead to failures. In many cases it becomes clear that there is no single cause or no single train of events. Instead, factors combine at a particular time and place to allow a failure to occur. Sometimes the ab-
sence of one factor may have been enough to prevent the failure. Sometimes, however, it is impossible to determine, at least within the resources allotted for the analysis, whether any single factor was key.

Failure analysts must look beyond the simplistic list of causes that some people still promote. They must keep an open mind and always be willing to get help from other experts. Many beginning failure analysis practitioners may have their projects defined for them when they are handed a small component to evaluate, and thus may be able to follow an established procedure for the evaluation. This is especially true when working for an original equipment manufacturer where much prior experience and knowledge of the physical factors that tend to go wrong with a component have led to established procedures. In that case, a particular analysis may not require extensive pretesting work. However, for the practitioner who works in an independent laboratory or must look at a wide variety of components, following a predefined set of failure analysis instructions may prove inadequate. Established “recipe”-type procedures are generally inadequate for the more advanced and broad-minded practitioner as well. A broad, systematic methodology is more appropriate.

Reasons behind the failure of a component, assembly, or structure can be multilevel. In other words, a failure should not be viewed as a single event. The actual physical failure—a fracture, an explosion, damage by heat or corrosion—is the most obvious. However, other levels of failures generally exist that allow the physical event to happen.

Consider the case of a simple failure whose direct physical cause was an improper hardness value. However, one or more persons allowed the improperly hardened component to be manufactured and used. Human factors generally are very difficult to investigate within a manufacturing organization, because cultures that allow a particular type of failure to occur usually will not have systems in place that enable simple remedies to be enacted for deeper-level causes. For example, if someone in an organization wants to investigate causes beyond the simple fact of improper hardness, it may be discovered that the inspection clerk was not properly trained to note reported hardness values when receiving materials. Changing a corporate culture to include better training and education is often difficult; many corporations are structured so that the people who are responsible for training do not have an open line of communication with those doing the investigation. This only increases the difficulty of implementing change to prevent failures.

**Failure Prevention.** Failure analysis of a physical object is often only part of a larger investigation intended to prevent recurrences. When taking the broadest view of what is required to prevent failures, one answer stands out: education. To reduce the frequency of physical failures, education must be instilled at multiple levels and on multiple subjects within an organization.
Education, of which job training is a single component, is what allows people at all levels of an organization to make better decisions in time frames stretching from momentary to careerlong. Many books contain exercises that help the reader to restructure knowledge into a more useful and accessible form. Other books help the reader learn to recognize incorrect lines of reasoning; an excellent example is *Tools of Critical Thinking: Metathoughts for Psychology* by D. Levy (Ref 1).

Specific levels of failure causes (Fig. 1) have been defined by Failsafe Network (Ref 2) as:

- **Root:** The true cause of failure—it encompasses the next three items
- **Physical:** The failure mechanism—fatigue, overload, corrosion, and so on
- **Human:** The human factors that lead to the physical cause
- **Latent:** The cultural/organizational rules that lead to the human cause

Clearly, many people involved with failure analysis incorrectly use the term “root cause” when what they really are referring to is a simple physical cause.

If failure analysis tasks are performed adequately, then the analyst ultimately should be able to list the causes found, show that the failure would have happened the way it did, and also show that if something different had happened at some step along the way, the failure would not have occurred or would have occurred differently. Unfortunately, this definitive demonstration of the failure is not always possible. Even a lengthy and thorough investigation can result in unknowns. The honest analyst is left to make a statement of the factors involved in allowing conditions that promoted the likelihood of failure. This is still a useful task, perhaps more useful than one that merely pins “blame” on a particular individual or
group. Understanding the factors that promoted a failure can lead to an understanding of exactly what is required to improve the durability of products, equipment, or structures. Understanding goes beyond knowledge of facts. Understanding requires integration of facts into the knowledge base of an individual so that the facts can be transformed into product and/or process improvement.

By now it should be clear that failure analysis is a task that requires input from people with many areas of expertise. A simple physical failure of a small object may be analyzed by a single individual with basic training in visual evaluation of engineered objects. However, going to the level of using the failure analysis to improve products and processes requires expertise in the various aspects of human relations and education, at the least. Failure analysis of a complex or catastrophic failure requires much more.

**Legal Ramifications.** People who perform failure analysis as part of their job function need to be aware of how their legal obligations are defined. Investigators who perform destructive testing on a failed component may sometimes be held personally accountable for the destruction of evidence. Company employees must learn to protect themselves. Investigators who were “just doing their job” have been successfully sued by parties that the judicial system determined had a legitimate interest in the outcome of the failure analysis project.

Never unquestioningly agree to destructively test a “failed” component. However, this places the destructive testing technician or engineer in a troublesome position, as it is sometimes difficult to see that a component has failed. Even if that information is given, relevant background details are often difficult to obtain, especially in a highly structured and hierarchical corporate culture. Pressure to finish the analysis quickly is common. People who request failure analysis work may not be aware that rushing ahead into the destructive portion of an investigation may well destroy much information and evidence.

Those who perform failure analysis work must realize that many people are still unaware of what failure analysts have to offer in terms of allowing clients or fellow employees to replace speculation with facts. The people who request failure analysis work may not be aware that rushing ahead into the destructive portion of an investigation may well destroy much information. This book is intended to demonstrate proper approaches to failure analysis work. The goal of the proper approach is to allow the most useful and relevant information to be obtained. All the valid approaches require planning, defining of objectives, and organization prior to any destructive testing. Simultaneous preservation of evidence also is required. It should now be clear that proper failure analysis cannot be done with input from only a single individual. Even someone only participating in the “straightforward” portions of the investigation of physical failure needs to know how his or her contribution fits into a bigger picture.
The competent failure analyst needs to know more than the failure analysis process and the tools used to support it. The competent failure analyst needs to understand the function of the object being analyzed and to be familiar with the characteristics of the materials and processes used to fabricate it. The failure analyst needs to understand how the product was used and the culture in which it was used. Communication skills are a must. When you ask a question, do you know for certain what the answer “yes” means? In some cultures, the word “yes” means “I heard the question” and does not imply that the answer is actually affirmative. The failure analyst must always be well versed in multiple disciplines.

Recognizing a Failure

A good basic definition of a failure is the inability of a component, machine, or process to function properly. However, this definition is not limited to things that break, causing a complete shutdown of a system. The concept of a failure is much larger. Can you identify a failure if you see one?

Does the situation in Fig. 2 appear to be a failure? Would you put your child in the sink for a bath with dishes? On the other hand, the child does appear to be on one side and not actually in with the dirty dishes.

Every one of us has watched a sporting event from the Olympics to Little League in which we see athletes succeed and fail in their endeavors. The sight of a dejected athlete looking at the ground with head in hands is a universal sign of failure. No one has to tell us the athlete failed, we know it.

Fig. 2 Is this a failure?
The beaver in Fig. 3 might be a victim of foul play—or, perhaps, a victim of overconfidence. How often has a supplier or coworker told you, “I know what I’m doing, you don’t have to warn me.” Next thing you know, there is a hole in a part where it doesn’t belong.
I could never determine if the photograph in Fig. 4 was an advertisement for the strength and durability of Mercedes-Benz trucks or a poster for traffic safety. I will always wonder where these folks were, how far they got, and if the man at the lower left got a lift or not. The trucks are obviously overloaded; it is only a matter of time before they will fail. Of course, no sensible person would run a machine over its capacity, right? Would a manufacturer run its machines beyond capacity just to get a few more parts per second?

In many failure investigations, the failure is represented by a broken piece of hardware like the shaft in Fig. 5. Anyone can look at this shaft and determine that it failed. In addition, the effect to the equipment is an instantaneous shutdown. However, that is not the only way by which failures occur.

Consider the propeller in Fig. 6. How did it fail? At first glance, some might assume that the propeller operates in salt water and thus failed due to corrosion of some kind. But look closely. The damage occurred only on the leading edges of the blades. The true failure mechanism is cavitation. You might think to yourself, “How was I supposed to know that? I’m not an expert on propellers.” To perform a failure investigation, you must become knowledgeable about the component or structure and all possible failure modes. And you need to consult with experts in the field.

As noted previously, a good definition of a failure is the inability of a component, machine, or process to function properly. The examples presented thus far indicate that a failure investigation may involve factors other than a broken component. Let us look at other, more detailed examples.

**F-20 Tigershark.** In the early 1980s, Northrop developed the F-20 Tigershark (Fig. 7) in response to a U.S. government interest in the private development of a tactical jet fighter specifically tailored to meet the se-
curity needs of allied and friendly nations. Unfortunately, the F-20 Tiger-
shark fighter was produced without a contract from the military.

The F-20 was inexpensive, reliable, and easy to maintain. Based on
comparisons with contemporary international fighters, the F-20 consumed
53% less fuel, required 52% less maintenance labor, incurred 63% lower
operating and maintenance costs, and offered four times the reliability. In
an era when comparable aircraft cost $15 to $30 million apiece, Northrop
designed one that cost about $1 million by eliminating all the technical
bells and whistles of other planes. It must have sold like hotcakes, right?

The company never sold a single F-20. Why? None of the allied and
friendly nations had asked for it. The U.S. military did not want it, either.
The military was used to the concept that it told the aircraft industry what
it wanted, and companies bid on the project. No one was used to the
aircraft industry simply providing an aircraft. The F-20 offered fuel effi-
ciency, cost efficiency, and better reliability, but nobody had asked for
those characteristics.

The last time I read about the F-20, only five still existed. To make
matters worse, one of the primary reasons the company was not able to

![Fig. 6 Propeller that failed by cavitation](image)

![Fig. 7 F-20 Tigershark, circa 1982](image)