CHAPTER 1

Systems Failure Analysis Introduction

THIS BOOK FOCUSES ON solving systems failures. Other books about failure analysis address component or material failures. Component failures are relatively easy to address (e.g., resistors can fail open or sometimes short circuit; metal parts can fail in fatigue, in tension, or in other discernable failure modes; plastic components can experience brittle fractures; etc.). If a capacitor fails, it is fairly simple to cut into it, examine it under magnification, and determine if it was subjected to too much energy (indicated by molten areas) or excess shock or vibration (indicated by mechanical separations).

While portions of this book cover component failure mechanisms, the focus here is on what can cause a system to fail. System failures can be induced by component failures (such as the ones mentioned previously), or they can occur as a result of complex component and subsystem interactions (without any parts failing). Finding the root causes of systems failures is far more difficult.

A few examples illustrate the nature of this challenge:

- When the United States lost the *Challenger* space shuttle in 1986, there was little evidence initially. The team investigating that accident had to evaluate thousands of potential causes and deduce the most likely cause.
- During the 1990 Gulf War, smart munitions received much of the credit for driving Saddam Hussein out of Kuwait. Smart munitions used laser target designators to guide them to their targets. The United States delayed Gulf War action for several weeks, however, because a key laser targeting system could not meet its accuracy requirements. All of the parts in this system conformed to their engineering requirements. No parts failed, but the system did not meet its requirements.

- A large municipal water treatment system designed to remove arsenic from public drinking water lowered arsenic levels to government-mandated requirements, but the system periodically experienced contaminant breakthroughs that allowed high contaminant levels to enter the water distribution system. No parts failed on this system either, yet the system suddenly stopped meeting its requirements.
- Aerospace engineers designed the Apache helicopter blade (a bonded stainless steel, carbon fiber, and titanium structure) to withstand a direct hit from high-explosive enemy projectiles. During combat operations over Iraq, an Apache helicopter blade actually took a direct hit from a Russian-designed ZSU-23/4 high-explosive warhead and returned home. Although the blades can withstand such punishment, their service life in normal operation was significantly less than required by the Army, and the rejection rate during production approached 50%.
- A warehouse storage system relied on wheeled iron structures to increase packing density in pallet storage racks. After thousands of these systems were built, the wheels started failing, requiring an expensive retrofit.

Some system failures are induced by component failures (for example, the warehouse storage system in which the pallet rack wheels failed, or the *Challenger* accident in which an O-ring failed). Some involve interfaces between parts (for example, the Apache helicopter blade failures in which the bonded interface failed). In other system failures, no single component fails, yet the system fails (for example, the laser targeting system or the municipal water treatment system).

Some systems failures are "showstoppers" (the production line comes to halt or a product fails dramatically in service). Others are recurring failures that are not as dramatic as the showstoppers, but they can be very expensive (for example, the high helicopter blade rejection rate during manufacture).

The challenge of systems failure analysis is to define the problem, identify the cause of the problem, select appropriate corrective actions, and then implement the corrective actions. Many organizations get that first step wrong. They do not adequately define the problem. If this is not done correctly, it is highly unlikely the failure analysis team will fix the problem.

In addition, training on systems failure analysis can be helpful at many levels in technical and manufacturing organizations. In addition to becoming knowledgeable in failure analysis procedures, tools, and technologies, failure analysis training instills a way of thinking that helps engineers, manufacturing specialists, purchasing specialists, field service technicians, and quality-assurance personnel become more successful.

The failure analysis process outlined in this book includes the following steps:

- Designate a failure analysis team with representatives from engineering, quality assurance, manufacturing, purchasing, and field service.

- Gather all related failure information.
- Review the aforementioned information and define the problem.
- Identify all potential failure causes using brainstorming, mind-mapping, Ishikawa diagrams, flow charting, the "five whys" technique, or fault-tree analysis.
- List each potential failure cause in the failure mode assessment and assignment.
- Use appropriate documentation reviews, interviews, design analyses, hardware analyses, and designed experiments to converge on the root cause.
- Identify potential interim and long-term corrective actions, and select the most appropriate corrective actions.
- Ensure corrective actions are implemented in all relevant areas (suppliers, inventory, work in progress, repair centers, and fielded systems).
- Follow-up after corrective actions have been implemented to assess corrective action efficacy.
- Evaluate other potential failure causes as corrective action candidates, and incorporate preventive actions where it makes sense to do so.
- Incorporate failure analysis findings into a failure analysis library, design and process guidelines, and troubleshooting and repair documents.

The Mast-Mounted Sight Challenge

One may think that defining the problem is an obvious and simple first step, but that is not always the case. Consider the mast-mounted sight (MMS) system developed and manufactured by McDonnell Douglas. The MMS looks like a basketball (Fig. 1.1) that sits on top of the helicopter blades. That basketball contains a television, a thermal imaging sensor, and a laser

Fig. 1.1 The mast-mounted sight (MMS) on a U.S. Army OH-58 Kiowa helicopter. The MMS contains a laser, a television, and an infrared sensor. Photo courtesy of U.S. Army Aviation Center, Fort Rucker, AL

target designator and rangefinder. Pilots use the MMS for finding targets with either a television or infrared sensor. When the target has been found, the MMS laser determines the range to the target and illuminates the target for the smart munitions.

The MMS laser and television use a window made of glass to see outside the MMS housing. The MMS thermal imaging sensor uses a separate germanium window. (The thermal imaging sensor infrared technology requires a window made of a different material due to its infrared energy requirements.) The MMS contains a boresighting system to align the thermal imaging sensor line of sight with those of the television and laser sensors. This is a critical part of the system and figures prominently in the following discussion.

McDonnell Douglas had been producing and delivering MMS systems to the U.S. Army for years. Prior to actually going to war, however, the Army decided to thoroughly wring out its MMS systems. During precombat testing, the Army found that the laser beam was misaligned enough to induce a miss, and this condition existed on all of its MMS systems. This was a huge problem. It threatened the United States' ability to go to war.

The engineers assigned to solve this system failure jumped to a conclusion and immediately defined the problem as laser misalignment. The failure analysis team attributed the cause to an MMS boresighting failure, and they spent several months attempting to find the failure cause in the boresighting portion of the system. These were smart people (the failure analysis team included engineers, physicists, scientists, and others), but they missed the first step of the problem-solving process: They did not define the problem correctly. To compound the situation, without attempting to identify all potential causes, the failure analysis team jumped to another conclusion when they decided that the cause must be in the boresighting system. The failure analysis team lost valuable time looking for the failure there.

After several months without making any progress, the McDonnell Douglas engineers and scientists decided to re-examine the test data. When they did this, they made two critical discoveries. The problem only appeared at cold temperatures, and both the laser beam and the television sensor were misaligned with the thermal imaging sensor. The laser beam and the television sensor were in alignment with each other. In other words, the problem was not laser beam misalignment with both of the other sensors, as the team previously thought. The team now recognized that the television and the laser were aligned with each other, but both were misaligned with the thermal imaging sensor. This was a different problem than the one the team had been attempting to solve.

Armed with this new (but previously available) information, the failure analysis team looked beyond the boresighting system. In particular, the team identified what part of the MMS system operated differently in cold weather. The team recognized that the laser and television sensor window used a different window-heating system than did the thermal imaging sensor. They next found that these heaters operated at different temperatures. Within hours, the failure analysis team concluded that the window heaters had induced the cold weather misalignment. McDonnell Douglas specified a simple software fix to correct the problem, and the Army implemented it on a worldwide basis a few days before engagement in the liberation of Kuwait.

The lessons inherent to the aforementioned experience are to ensure that the problem is accurately defined, that conclusions are not hastily made, and that all potential causes are considered before a fix is attempted.

The Systems Failure Analysis Process

The challenge in approaching a system failure is to:

- Accurately define the problem
- Identify all potential failure causes
- Objectively evaluate the likelihood of each failure cause
- Take steps to prevent these failure causes from occurring

This is an extremely important concept, so much so that it is highlighted as follows:

> *The systems failure analysis approach requires defining the problem, identifying all potential failure causes, objectively evaluating each potential failure cause, and implementing actions to preclude recurrence.*

This approach works well for several reasons.

Focusing on identifying all potential failure causes (without arbitrarily or subjectively eliminating any during the initial analysis phase) opens a universe of potential failure causes. These probably would not be considered if the failure analysis team jumped to and addressed only the most likely causes. Several techniques for identifying all potential failure causes are covered. For now, it is important to recognize that the objective is to identify all potential causes, not just the perceived obvious ones.

If the failure being analyzed is a recurring or intermittent condition, the failure causes will almost certainly be subtle. Identifying all potential causes forces the investigator to look away from the obvious causes. If the cause of a recurring or intermittent problem was obvious, would not prior failure analysis efforts have already identified and corrected it?

When the failure analysis team focuses on identifying all potential failure causes, the failure analysis team will identify potential causes beyond those that caused the failure under investigation. Even if the failure analysis team determines that these other hypothesized failure causes did not cause the failure being investigated, this approach creates numerous improvement opportunities. The failure analysis team can address the other hypothesized causes and prevent them from recurring as well.

The Four-Step Problem-Solving Process

In subsequent chapters, this book introduces and develops several sophisticated approaches for identifying and evaluating potential failure modes, developing potential corrective actions, and then selecting the best corrective actions. All of these can be condensed, however, to the simple four-step problem-solving process shown in Fig. 1.2.

Each of these steps is examined as follows.

What Is the Problem? Defining the problem sounds easy. It frequently is not. Based on experience in hundreds of organizations spanning several industries, this is a step that many people miss (consider the McDonnell Douglas MMS example described previously). It is very easy to focus on symptoms or to jump to conclusions regarding potential causes and thus miss the problem. Therefore, it is highly recommended to spend enough time on this step. All members of the failure analysis team should agree that the problem has been accurately defined before moving on to the next step.

What Is the Cause of the Problem? After defining the problem, the failure analysis team can use several technologies to identify potential failure causes. It is important to recognize that this is not a simple process. It is also important to realize that this question is not always treated as objectively as it should be. Consider these scenarios:

- One or more of the participants in a failure analysis meeting feels confident that they know what caused the failure before all of the facts are available.
- Potential failure causes are dismissed without careful consideration.
- The people in such discussions jump ahead to define corrective actions before the failure causes have been confirmed.

During this step of the four-step problem-solving process, the failure analysis team should focus on accomplishing two objectives. The first is to identify all potential failure causes. The second is to objectively evaluate the likelihood of each. This book develops a structure for doing both.

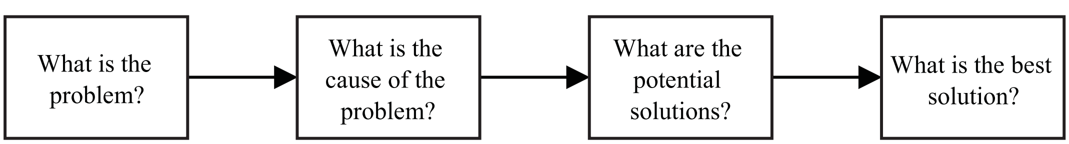

Fig. 1.2 The four-step problem-solving process guides the systems failure analysis technologies and approach addressed in the remainder of this book.

To help identify all potential failure causes, the following methods are covered:

- Brainstorming
- Ishikawa diagrams
- The "five whys" approach
- Mind mapping
- Fault-tree analysis

All of these approaches for identifying potential failure causes are good ones, but fault-tree analysis is preferred in many cases for its systematic coverage. After the failure analysis team has identified all potential failure causes, the team focus should then shift to objectively evaluating each. This book describes several technologies covering this important part of the systems failure analysis process.

What Are the Potential Solutions? Identifying the potential solutions can only occur after the causes have been identified, and there are categories of corrective actions ranging from highly desirable to those that are not so desirable. Highly desirable corrective actions are those that remove all potential for human error. These corrective actions can include such things as designs that prevent incorrect assembly or processes with capabilities that guarantee outputs within acceptable ranges. Less desirable corrective actions rely on people doing things correctly. Examples of these include additional inspections to eliminate defects (an approach highly likely to allow defects to escape, as is explained in later chapters), assembly sequences that can induce defects if not followed exactly, and other actions similarly dependent on people doing things perfectly.

What Is the Best Solution? The aforementioned guidance notwithstanding, the best solution may not always be the one selected for immediate implementation. Sometimes, product or process redesigns are not feasible for cost or schedule reasons. Sometimes, additional inspections or screenings are the only avenue available in the short term. In many cases, the failure analysis team may opt to implement interim, less desirable corrective actions immediately, to be followed up by longer-term, more desirable corrective actions that absolutely preclude failure recurrence.

As mentioned previously, the failure analysis team should not restrict its thinking only to the actual failure cause. The failure analysis team should also consider corrective actions to prevent the other hypothesized causes from inducing future failures. The failure analysis team should also go beyond the system that failed. In many cases, other identical systems will have already been fielded or placed in storage. Other systems may be in production. The failure analysis team should evaluate all product areas to determine if these areas should incorporate the corrective actions applied to the failed system. Finally, the failure analysis team should consider other similar system designs susceptible to the same problems. Where appropriate, these also receive the same corrective actions.

The Failure Analysis Team

Many organizations assign failure analysis responsibilities to a single department (typically engineering or quality assurance). This is a mistake. Experience has shown that the most effective failure analysis teams include engineers, quality-assurance specialists, manufacturing technicians, purchasing personnel, field-service personnel, and others. The inclusion of an organization's major disciplines ensures that no single department subjectively and unilaterally concludes the fault lies outside their area of responsibility. A system design, manufacturing process, tooling, or inspection approach can induce failures. Components or subassemblies provided by suppliers can induce failures. The environment in which the system is operated can induce failures. There are many other factors that can induce failures. For example, manufacturing organizations typically purchase more than half of their product content; including a purchasing representative on the team ensures quick and accurate communication with suppliers. The failure analysis team will need to assess the product pedigree, which may require additional testing or inspection; including a quality-assurance representative will expedite obtaining this information. In some cases, failures occur even when all parts are conforming to the engineering drawings and the system has been properly assembled; in such cases, it makes sense to have an engineer on the team to assess design adequacy.

There is a synergy that emerges when a failure analysis team composed of different specialists defines the problem, identifies and evaluates potential failure causes, develops potential corrective actions, and selects the best corrective actions. Incorporating representatives from each critical area fosters problem-solving synergy and ensures that the organization's strengths and capabilities are appropriately focused.

Summary

The four-step problem-solving process is a basic framework for systems failure analysis. The failure analysis team should start by gathering all available information and converge on a clear, agreed-upon problem definition. The next step is to identify all potential failure causes. When the potential failure causes have been identified, the failure analysis team should objectively evaluate each. This will guide the failure analysis team to the cause of the system failure under investigation. The failure analysis team should evaluate and implement corrective actions for the confirmed cause of the failure and for other potential failure causes, to prevent other future failures. The failure analysis team should include engineering, manufacturing, quality assurance, purchasing, field service, and representatives of other disciplines to ensure problem-solving synergy and objectivity.

Example for Group Discussion. Military range-finding and target-designation lasers (such as the MMS) typically use a 1.06 μm wavelength laser beam, which is hazardous. The 1.06 μm wavelength laser beam can permanently blind a human. For this reason, some military lasers convert the laser energy to a nonhazardous 1.54 μm wavelength for training exercises. The LANTIRN laser system accomplishes the wavelength shift with the use of a device called a Raman cell (named for the scientist who discovered the effect). The Raman cell is a sealed titanium tube containing 1000 psi methane gas and windows at either end. The Raman cell converts 1.06 μm wavelength laser energy to a 1.54 μm wavelength.

During production of the LANTIRN laser assembly, technicians direct the 1.06 μm wavelength beam into the Raman cell. The assembly technicians then adjust the amount of energy entering the cell to meet required Raman cell output energy levels, because some energy is lost when the beam travels through the cell.

During early LANTIRN production, approximately 10% of the Raman cells failed when the technicians adjusted the laser energy. When the technicians adjusted the energy level, some of the Raman cell windows developed dark-brown burn spots. These burn spots can result from:

- The windows being contaminated (i.e., they are dirty)
- Too much laser energy passing through the windows
- A combination of too much laser energy and contamination

The laser system manufacturer accepted the 10% rejection rate, because they considered this to be part of the "black art" of laser manufacturing. After several months, however, the Raman cell rejection rate due to burn spots crept upward until it hit 50%. The manufacturer could not accept a rejection rate this high.

Based on the aforementioned:

- How should the problem be defined?
- What are the causes of the problem?
- What are the potential solutions?
- What is the best solution?

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