New Tools for Failure and Risk Analysis

Anticipatory Failure Determination$^{®}$ (AFD) and the Theory of Scenario Structuring

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Anticipatory Failure Determination® (AFD) and the
Theory of Scenario Structuring

Stan Kaplan, Svetlana Visnepolschi,
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Abstract

This book introduces the reader to a new method designed to help various types of risk analysts in their continuing efforts to reveal potential failure modes in systems, manufacturing plants, processes, etc., before they make their existence known in harmful or unpleasant ways. This new method, called Anticipatory Failure Determination® (AFD), is an application of *I-TRIZ* (an advanced form of the Russian-developed Theory of Inventive Problem Solving) to Risk Analysis, and, more specifically, to the subset of Risk Analysis that we refer to here as the Theory of Scenario Structuring. This book will present AFD® within the context of the Theory of Scenario Structuring, compare it to existing methods such as Failure Modes and Effects Analysis (FMEA) and Hazard and Operations Analysis (HAZOP), and assert the value of the new viewpoints that AFD brings to the subject of Risk Analysis. We will suggest that AFD is particularly suitable to a class of scenarios of current importance, namely, those involving human error, sabotage, terrorism, and such. We will also suggest that the AFD approach can be used to codify and organize the world's accumulated experience in the operation of plants and systems of various types, and to make this knowledge readily available to new designers. Further, this can be done in such a way that the mistakes, accidents, and oversights of the past need not be repeated before the appropriate lessons are learned and become routine parts of engineering culture.

Introduction

The purpose of Risk Analysis (RA) is to reveal and identify potential failure modes (or "scenarios") in our systems and operations so that they may be corrected before they manifest. To this end, RA comprises an arsenal of methods, as shown in Figure 1. Among these, the best known are: Failure Modes and Effects Analysis (FMEA), Hazards and Operations Analysis (HAZOP), Fault Trees (FT) and Event Trees (ET). The purpose of this book is to introduce the reader to a new method, *Anticipatory Failure Determination® (AFD)*, which provides a valuable addition to this arsenal. We shall discuss the pros and cons of AFD® compared to traditional methods, and provide a conceptual framework, called the *Theory of Scenario Structuring*, within which all RA methods can be seen as variations on the same basic principles.

The new method, AFD, is the application to Risk Analysis of *I-TRIZ*, an advanced form of the Russian-developed Theory of Inventive Problem Solving (known by the acronym TRIZ). [1,2]. The relevance of this theory to RA is rooted in the fact that *revealing and identifying failure scenarios* is fundamentally a creative act, yet it must be carried out systematically, exhaustively, and with diligence. And I-TRIZ is uniquely equipped to do this, because it provides a systematic approach to finding creative solutions to inventive problems.

AFD can be utilized in various areas of human activity – technology, business, even everyday life – whenever there is a need to:

♦ Reveal the root causes of an error, unsuccessful action, manufacturing failure, or accident.

♦ Predict future problems, accidents, errors, etc.

♦ Develop effective, simple ways of preventing these problems.

1. FMEA (Failure Modes and Effects Analysis)
2. HAZOP (Hazard and Operability Analysis)
3. PHA (Preliminary Hazards Analysis)
4. Threat Analysis
5. Vulnerability Analysis
6. Fault Trees
7. Event Trees
8. Event Sequence Diagrams
9. Etc.

Figure 1. Tools for Revealing Failure Scenarios

Chapter 1
Risk Analysis and the Theory of Scenario Structuring

1. Risk Analysis (RA)

Risk Analysis, as a formalized subject, has existed for about three decades. During this time it has experienced a rapidly-growing popularity, which at present shows no signs of slowing. One reason for this growth is that RA applies not only to engineering problems – i.e., to the reliability of our machines and manufacturing plants, etc. – but also to business, financial and military operations; marketing campaigns; research projects; organizations; social, political, economic, defense, and educational systems; international relations; environmental management; food safety; and personal health. In other words, RA applies wherever there is risk – which is, essentially, everywhere.

2. Quantitative Risk Analysis (QRA)

For about the last two and a half decades, risk analysts have emphasized the need, for purposes of decision making, to include not just the *identification* of possible failure scenarios, but also the *quantification* of the likelihoods and consequences of these scenarios. With this inclusion, the subject of RA has evolved to the point where it is generally referred to as Quantitative Risk Analysis, Quantitative Risk Assessment (QRA), or, sometimes, Probabilistic Risk Analysis (PRA).

2.1. The Quantitative Definition of Risk

As part of this evolution, the term "risk" itself has been defined quantitatively [3], as the answers to the following questions:

(1) What can go wrong (with the system or operation under study)?

(2) How likely is it that this will happen?

(3) If it *should* happen, what will be the consequences?

A single answer to the first question – "What can go wrong?" – is called a *failure scenario* or *risk scenario*. Assuming there are multiple scenarios, the ith such scenario is denoted by S_i.

The answer to the second question – "How likely is it that this will happen?" – must be answered for each scenario and is denoted by L_i.

The consequences or damages that result from the ith scenario are called X_i, which provides the answer to the question, "If it should happen, what will be the consequences?" The triplet $<S_i, L_i, X_i>$ therefore constitutes a single, distinct answer to the three risk questions. We can enclose this triplet in brackets to indicate a mathematical *set*: $\{<S_i, L_i, X_i>\}$. If we append a subscript, c, to the brackets, we have denoted the *complete set* of triplets, and thus have denoted the definition of risk [4]:

$$R \;=\; \{<S_i, L_i, X_i>\}_C$$

By "complete" we mean that, in assessing risk, we wish to identify all possible scenarios – or at least all the important ones.

Determining L_i and X_i may be thought of as the quantitative part of Quantitative Risk Analysis; identifying S_i is the qualitative part. Our main interest in this book is the *qualitative* part, which is where AFD makes its contribution. Nevertheless, we shall now present some key ideas from the quantitative part. The reason for this is to discuss quantification, partly for the sake of completeness, and partly because quantification, in one form or another, is an essential component to achieving true understanding. Thus, to simply identify an S_i as a possibility is not sufficient to enable us to make decisions and take actions with respect to that S_i. To understand the scenario to the extent that we are able to decide and act requires that we quantify its likelihood and consequences.

This does not mean, however, that we must quantify everything to six significant digits. Rather, we need only quantify in a form appropriate to the decisions that must be made. Thus, quantification can be carried out at various levels of thoroughness, and may differ depending on context. This idea is discussed further in section 3.1.

3. Quantification of L_i and X_i

The concept of *damage* can be captured quantitatively in units such as lives lost, number of injuries, repair cost, etc. – whatever is appropriate to the particular scenario.

Similarly, the intuitive notion of *likelihood* can be captured quantitatively by the parameter *frequency*, measured in units of occurrences per trial (for discrete operations such as the launch of a space vehicle), or in occurrences per unit time (for a continuously operating system such as a power plant, for example).

3.1. Levels of Quantification

It is worth noting that various *levels* of quantification are used in Risk Analysis (Figure 2).

1. Verbal	e.g., high, medium, low
2. Ordinal	e.g., 1 to 10
3. Point Estimate	$\hat{\phi}$
4. Bounding Estimate	$[\phi_1, \phi_2]$
5. Probabilistic	$p(\phi)$
6. Evidence-Based	$p(\phi|E)$

Bayes' Theorem

$E_1, E_2\ldots$
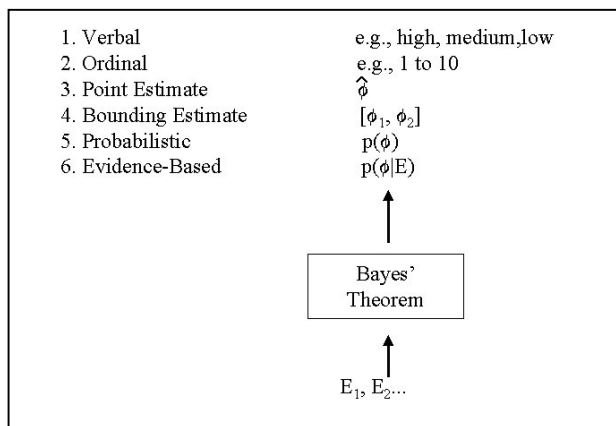
Figure 2. Levels of Quantification

There is the *verbal level* at which damage and frequency are rated (typically) as high, medium, or low. The next level is what we might call a *semi-quantitative* or *ordinal* level, at which, for example, damage might be rated on a scale of one to ten. This is followed by what we can refer to as the *point estimate* level, at which we give our "best guess" numerical value for the actual damage or frequency. Next is the *probabilistic* level, at which we acknowledge that we do not know the exact value of damage or frequency for a given scenario, but are not totally ignorant either. Therefore, we express what we do and do not know about these parameters in the form of probability curves (see Figure 3). Such curves are called *state of knowledge probability curves*.

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3.2. The Evidence-Based Approach

At this point the question arises: "How do we obtain these probability curves?" The answer has traditionally been found, to 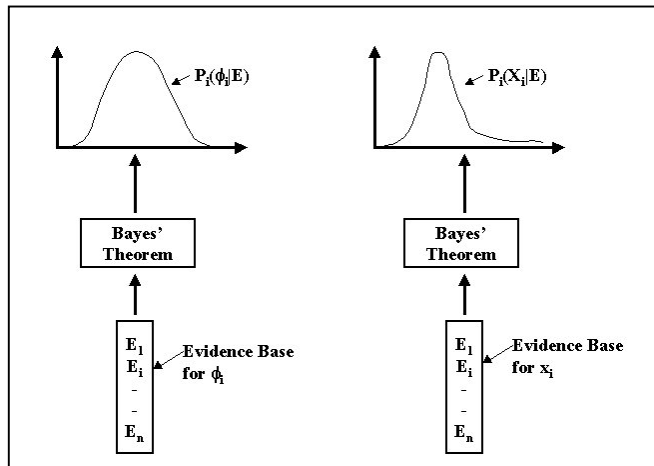a large extent, by gathering the opinions of experts. We can now, however, elevate the discipline of QRA to a new level by means of what we call the *evidence-based approach* [6,7]. In this approach we explicitly compile a list of all evidence items, E_j, relevant to the frequency or damage (Figure 3). These items are then processed, one at a time, through Bayes theorem, which is the fundamental mathematical/ logical principle governing the process of evaluating evidence. In this way we obtain the final probability curves.

Figure 3. "Evidence-Based" Approach

We call the curves obtained in this way *evidence-based probability curves*, and we regard them as the highest, most disciplined form of quantification. Our motto, in developing these curves, is therefore:

Let the Evidence Speak

rather than the opinions, personalities, positions, politics, moods, or wishful thinking of the people concerned.

3.3. The Purpose of Quantification

The purpose of quantifying Li and Xi, is, of course, to help us make decisions on which scenarios need attention, and thus we do not waste valuable resources reducing the frequencies of, or damages from, scenarios that are of little significance. The level of quantification chosen should be consistent with, and sufficient for, this purpose. The "full-blown" mechanics of the evidence-based approach should be used where major decisions are at issue, and even in less critical circumstances should be kept in mind.

4. Finding Scenarios: The Theory of Scenario Structuring

As with the quantification of L_i and X_i, the identification of the set of S_i can also be carried out at various levels of detail and thoroughness. There are many traditional methods in use. The best known of these are Failure Modes and Effects Analysis (FMEA), used in the automotive and aerospace industries, Hazards and Operations Analysis (HAZOP), used extensively in the chemical industry, and Fault and Event Trees, widely used in the nuclear energy industry. For any real-world situation the set of possible failure scenarios can be very large. In practice, the challenge is to manage this set – to organize and structure it so that the important scenarios are explicitly identified, and the less important ones grouped into a finite number of categories.

It can be said that, on a fundamental level, the process of identifying and structuring possible failure scenarios is part science and part art, often requiring considerable creative imagination to visualize the possible scenarios. Thus any new approach to this process, let alone a structured method, is welcome, as it might offer a point of view from which scenarios can be seen that were not previously apparent.

Such is the case with AFD. It is not only a new method, but as we shall see, it contributes a radically different viewpoint, and uses an approach that is significantly different from, while complementary to, those of the traditional methods. The best way to understand this is to view these different methods as special cases within the context of what we shall call the *Theory of Scenario Structuring*. This will be our task throughout the next few sections. We begin by presenting the principles and language of this theory.

4.1. Principles of Scenario Structuring

1. The Principle of S0

This principle asserts that, before attempting to do a risk assessment for some system or activity, one should be very clear on exactly what that system or activity is. In other words, for the failure scenarios to be understood, the "success" (or as-planned) scenario must be clearly specified. We denote this scenario by S_0.

S_0 can be described in various diagrammatic forms. Examples are given in Figures 4 to 7.
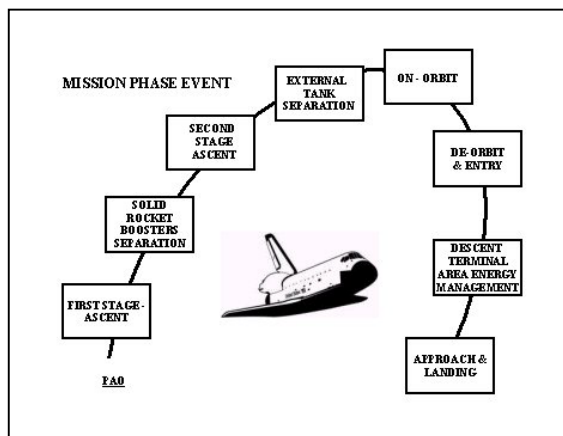
Figure 4. Mission Phase Risk Analysis

Figure 5. Top Level Project Schedule Diagram for Arctic Gas Pipeline Project
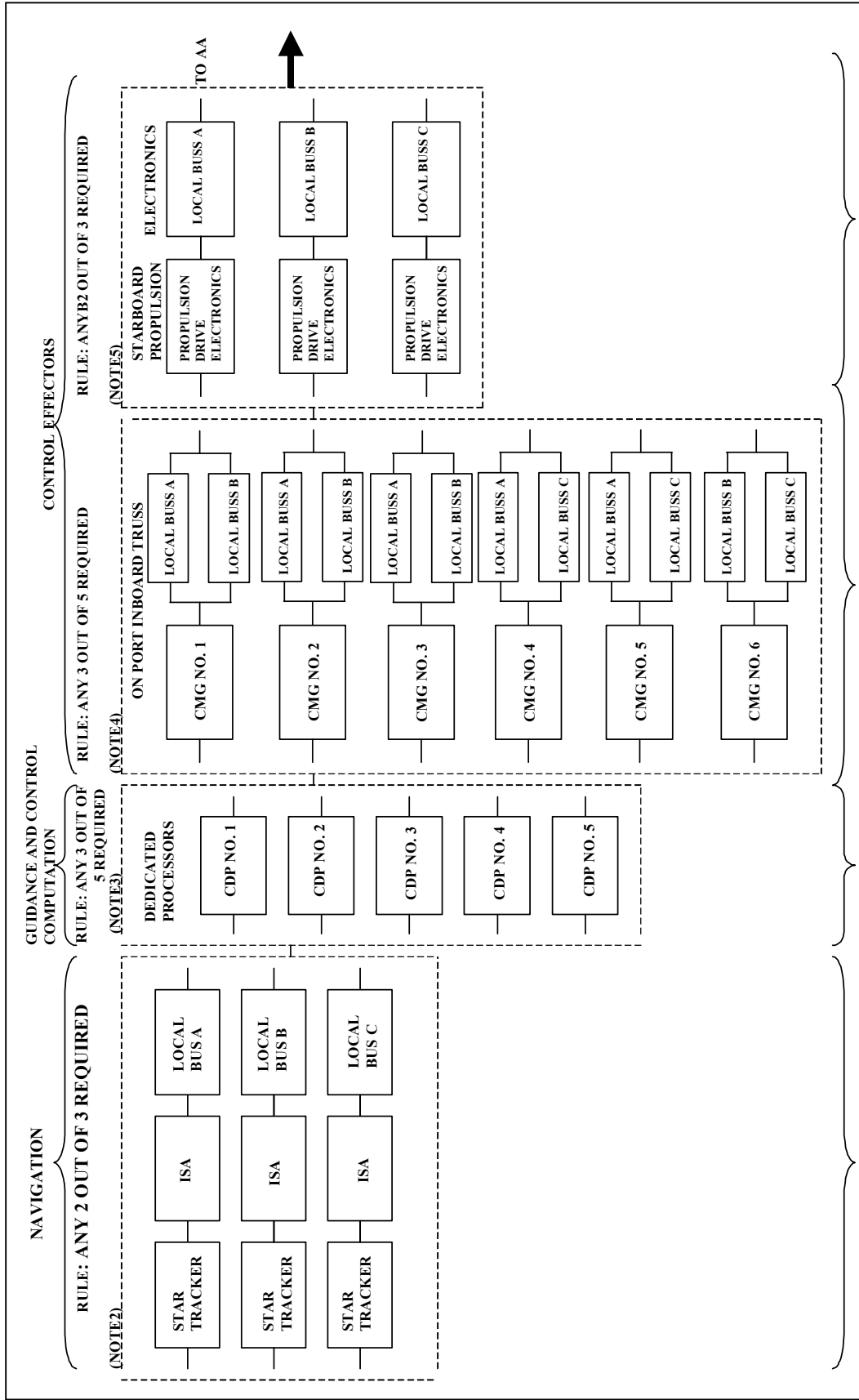
Figure 6. Reliability Block Diagram
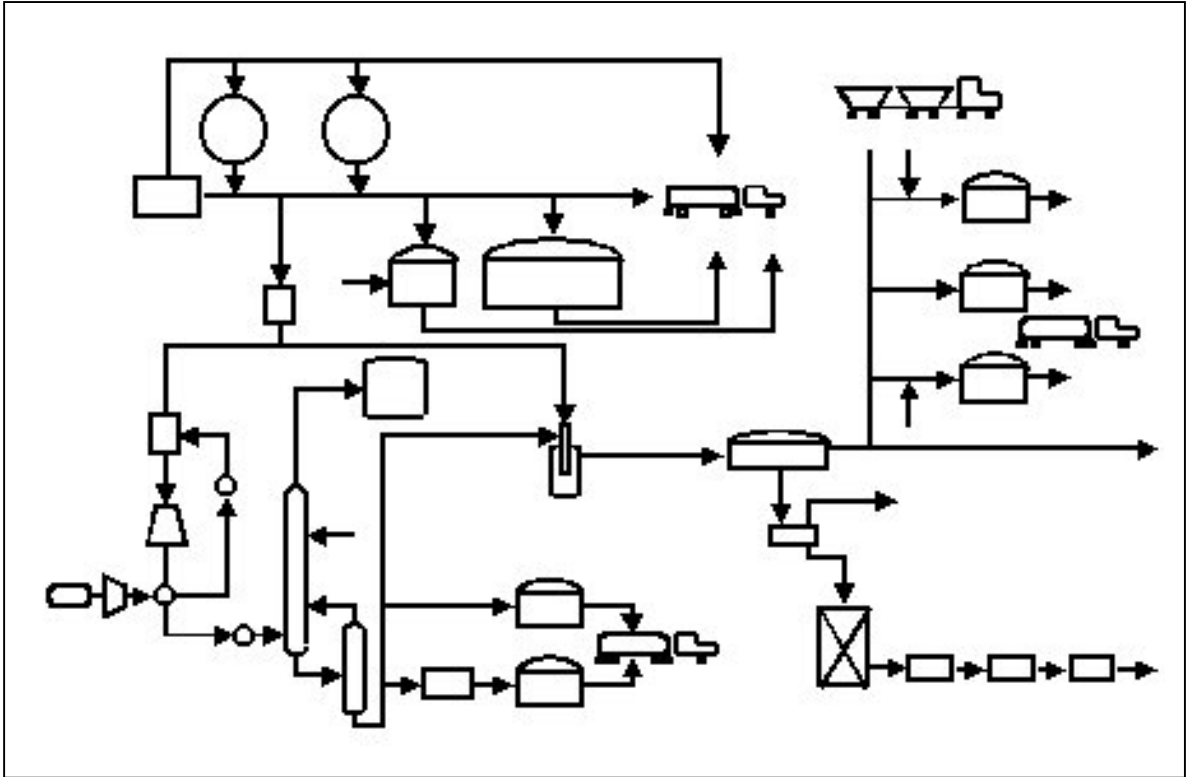
Figure 7. Plant Process

It is useful as well to think of S_0 as a trajectory in the "state space" of the system (as shown in Figure 8) where time, t, is a parameter along this trajectory. In terms of this diagram, we can state a second principle of our theory as:

2. The Principle of Initiation

Since S_0 is the as-planned scenario, any failure scenario, S_i, which departs from this plan, must have a point of departure – a point at which something occurs that results in the departure (see Figure 9). This something is called the *Initiating Failure* or *Initiating Event* (IE). The IE can be *internal* – i.e., a failure within the system itself, such as a stuck valve or a computer crash – or it can be *external*, i.e., originating outside the system, such as an earthquake.
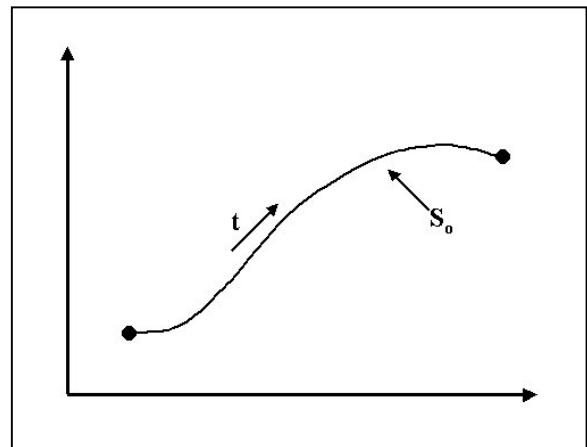
Figure 8. Scenario S_0 Viewed as a Trajectory in the State Space of the System
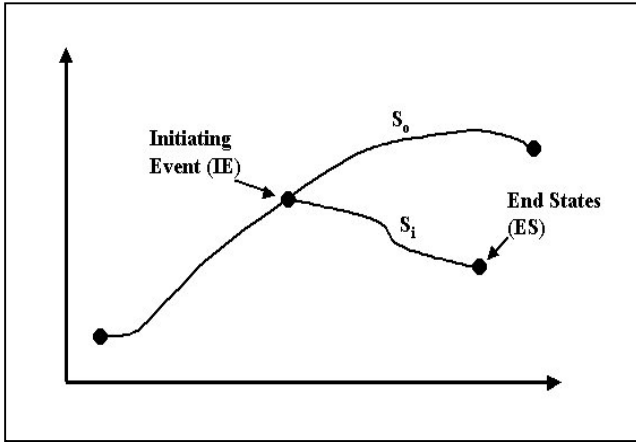
Figure 9. The Risk Scenario S_i as a Departure from S_0

3. The Principle of Emanation

From each IE, an entire outgrowth of related scenarios emerges (see Figure 10), which we refer to as a *scenario tree*. Each path through the tree represents a particular scenario, depending on what happens after the IE. For example, if the IE is "power supply fails," then immediately following the IE is a branch point at which either "backup power is initiated" or "backup power fails." In the case of the former, a relatively

benign scenario results. (Indeed, this might be thought of as a success scenario, given the severity of the IE.) If backup power also fails, however, then the scenario could lead to serious consequences.

Each branch of the tree continues until it reaches the "end" of that scenario; the state of the system at this point is called the *end state*, ES. If this state is benign, we might label it a BES. If harmful, we can refer to it as an HES.

Figure 10. Scenario Tree Emerging from the Initiating Event

4. The Principle of Unending Cause-Effect

Every cause/effect chain extends indefinitely in both directions. What we call an end state for one scenario is also the initial state for whatever happens downstream. The stuck valve that is our IE may be the ES of a chain that began with the inattention of the worker who manufactured the valve, and so on.

5. The Principle of Subdivision

Every scenario that we can describe with a finite set of words is itself a set of scenarios, i.e., it can be broken down into sub-scenarios. For example, the scenario "pipe break" can be broken down into "axial break," "transverse break," "puncture," etc. Conversely, every scenario is a sub-scenario of a larger scenario (except, of course, the scenario that is the set of all scenarios).
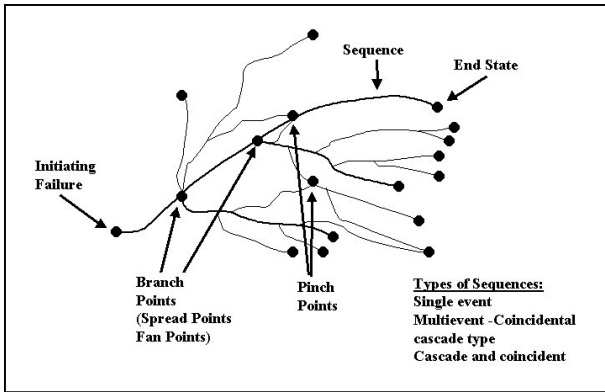
**Figure 11. Emanation of Scenarios
from the Initiating Failure**

6. Pinch Point Principle

In addition to *branch points*, a scenario tree may contain *pinch points* (see Figure 11). The downstream tree from a pinch point is independent of the upstream path by which that point was reached. For example, once a shipment of contaminated meat leaves the packing plant, the downstream consequences will be the same, regardless of which cow was diseased. (This assumes, of course, that the amount and type of contamination is the same.)

A pinch point in a scenario tree may also be called a *middle* (or *mid-*) *state* (MS).

7. Fault and Event Trees

Just as a pinch point has several incoming paths, an ES may have multiple scenarios leading to it, including scenarios from different IEs (Figure 12). This suggests that for a particular HES we can draw an *incoming scenario tree*, as in Figure 13. Such a tree is also called a *fault tree*. The outgoing scenario trees from the IEs are also called *event trees*. Trees with mid-states, such as in Figure 14, can be called *mixed trees*. Figure 15 shows an elaboration of the mixed tree concept in which the branch points of an event tree are fed by subsidiary fault trees.
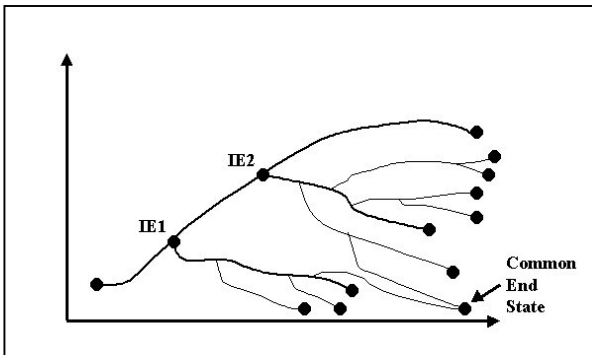
**Figure 12. Branches From Two Different
Trees Can End at the Same End State**
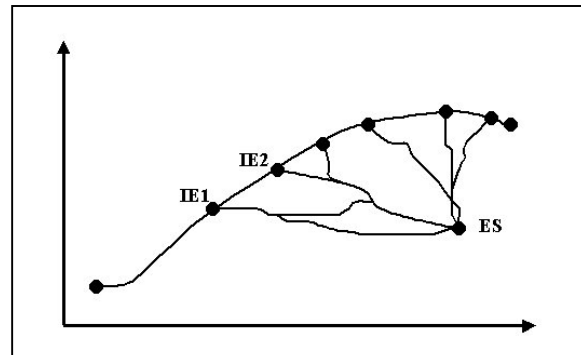
Figure 13. Incoming Scenario Tree
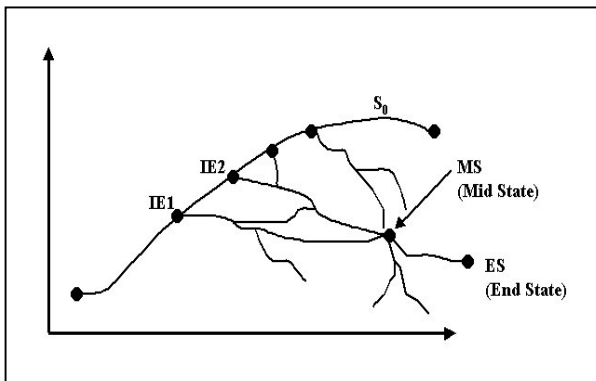
Figure 14. "Mixed" Scenario Tree
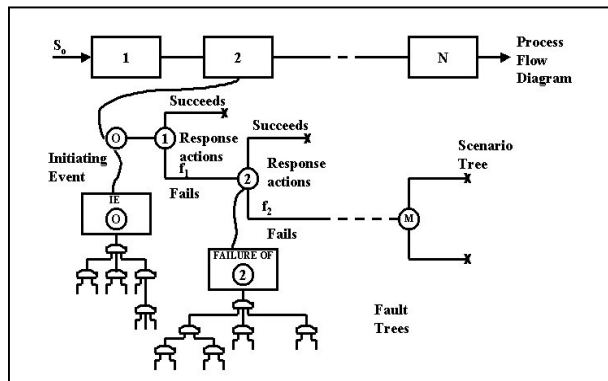
**Figure 15. Combined Use of Forward
and Backward Trees**

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Figure 16a shows the outgoing tree from the mid-state "buckle during J-lay" in the construction of an undersea pipeline. The incoming tree that leads to this mid-state is shown in Figure 16b.
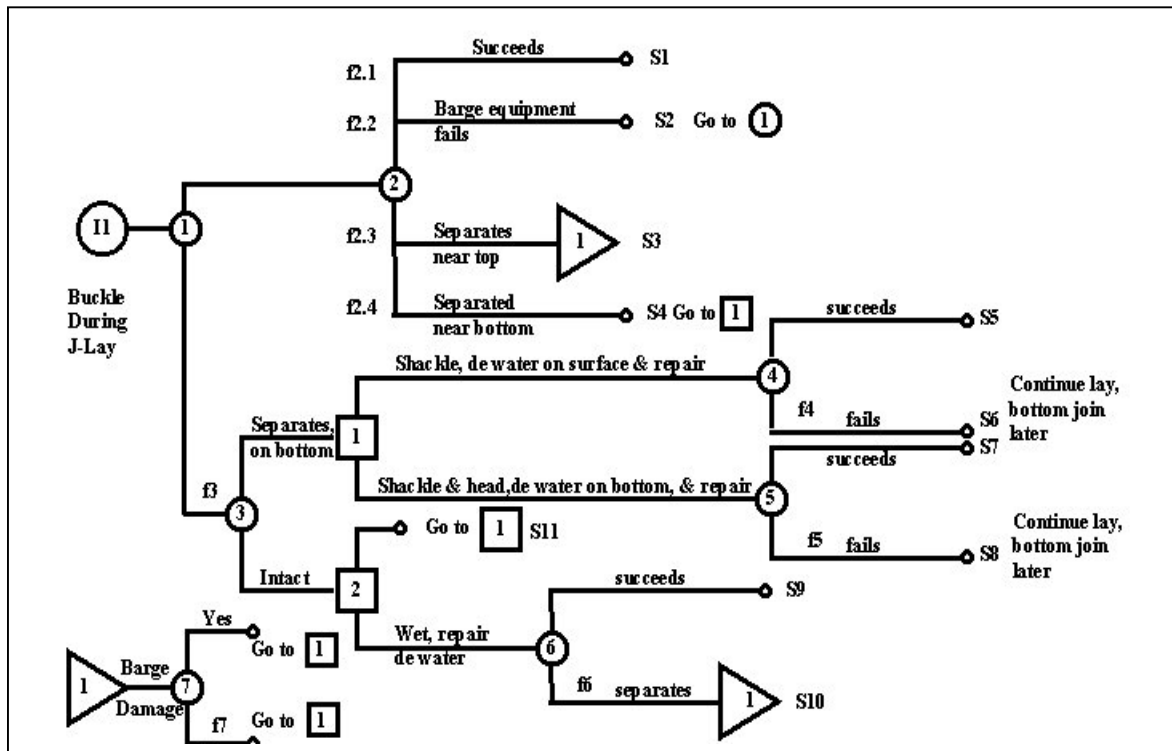
Figure 16a. Scenario Tree for Response to Buckle During J-Lay
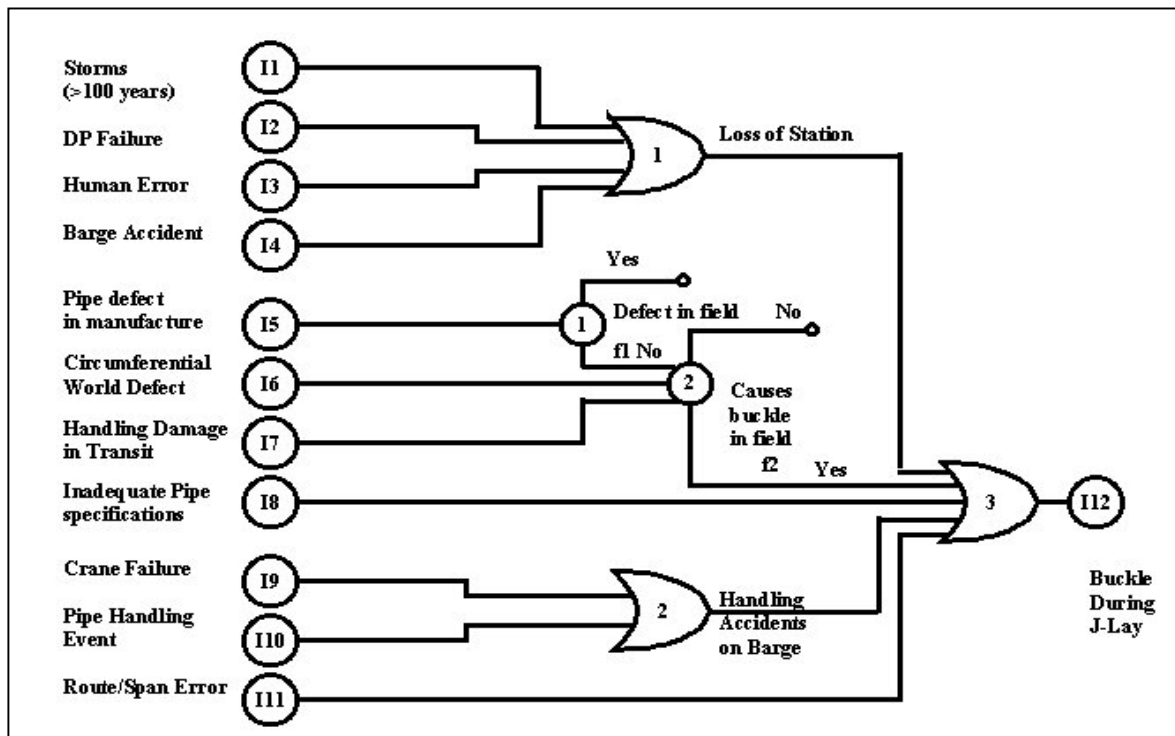
Figure 16b. Incoming Scenario Tree for Buckle During J-Lay

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8. The Principle of Resources

We shall adopt the term *resources* to denote all the substances, fields, configurations, time or space intervals, or other factors present in a situation. Given this definition, we can state the following principles: If all the resources necessary for an IE are present in a situation, then that event will occur; and conversely, If at least one of the necessary resources is *not* present, then that event will *not* occur. These principles are, of course, nothing more than tautologies, just as the Principle of Initiation (Principle 2) is a tautology. Nevertheless, as will become evident below, these simple principles will be of great value in guiding our search for, and explanations of, failure scenarios. Moreover, they illustrate the most effective and simple way to eliminate a failure: *remove from the system (or at least disable) one of the necessary resources.*

5. The Three Basic Methods for Finding Scenarios

Based on the above, we may now identify three basic methods for finding scenarios:

1. Find the possible IEs and draw the outgoing trees from each.

2. Find the important ESs and draw the incoming trees to each.

3. Find important mid-states and draw the incoming/outgoing trees to each.

We can now observe that FMEA utilizes method 1, where the failures of individual components (in an automobile, for example) constitute the IEs. HAZOP is an application of method 3, starting from mid-states such as "too much flow" or "temperature too low" in a given length of pipe, and then working both upstream – "How could this happen?" – and downstream – "What happens as a consequence of this?" Pest risk assessments [8,9] most often utilize method 2. Nuclear plant assessments rely heavily on all three methods, as well as the *subsidiary tree* idea of Figure 15, in which the main tree is an event tree with subsidiary fault trees drawn for the failing branches of key branch nodes.

5.1. Example: Failure Modes and Effects Analysis (FMEA) and the Issue of Completeness

As was stated earlier, FMEA is an example of the application of method 1. In both FMEA and its variant, Failure Modes and Effects Criticality Analysis (FMECA), IEs are defined as failures of individual components of the system. Thus, in an automobile, one would work through the entire machine, asking, "What would happen if *this* part failed? If *that* part failed?," etc.

To present this approach in more general terms, we can observe that any system may be subdivided into a finite number of components or parts. These are represented along the vertical axis in Figure 17, where we can think of this axis as a "space-like" axis.

Similarly, if a particular mission, S_0, has distinct phases of operation (as in Figure 4, for example), then these phases may be represented along the horizontal axis as is done in Figure 17, forming a time-like axis. Each box in this coordinate grid can now be taken to represent an IE. For example, the i,j^{th} box would represent the IE: the ith component fails during the jth phase. Since the number of phases and components are finite, there are a finite number of boxes in the plane of Figure 17, and thus we have defined a "complete" and finite set of IEs.

If we now draw outgoing scenario trees from each IE, and do this in such a way that the set of paths in each tree represents a complete set of scenarios emerging from that IE, then the set consisting of all the scenarios in all the trees emerging from the complete set of IEs is a *complete set of scenarios,* or S_i.

And thus we have shown at least one way to satisfy the requirement of the subscript *c* in our definition of risk as given by Equation (1).
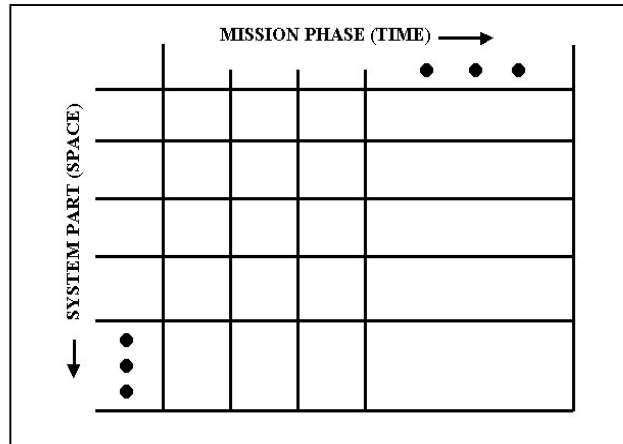
Figure 17. Two-dimensional Coordinate Axes in the Space of Initiating Failures

5.2. Example: Fault and Event Trees

Fault trees and event trees are used extensively in the nuclear industry. Fault trees are incoming trees to a given end state, and thus are examples of basic method number 2. In a nuclear power plant the end state of greatest interest is "melted fuel elements." The fault tree is generated by working backward from the end state. Thus we ask: "How can a fuel element get hot enough to melt?" Well, either the power production of that element goes up, or the cooling of that element goes down. How can the cooling go down? Either there must be a loss of coolant or of motion (flow) of the coolant, a loss of heat capacity of the coolant, a loss of heat sink, or a loss of thermal contact between the coolant and the element. So at this point the fault tree has five branches. Each of these branches is now carried backward by successively asking the "How could that happen?" question.

Event trees are outgoing trees from initiating events (basic method number 1). In nuclear plant risk work there is a standardized set of IEs that are examined: pipe break, loss of offsite power, turbine trip, etc. "External" initiating events, such as earthquake, windstorm, flood, fire, airplane crash, etc. are also typically included in the analysis.

5.3. Example: Hazard and Operations Analysis (HAZOP)

HAZOP, used extensively in the chemical process industry, is an example of method number 3, mentioned at the beginning of Section 5. HAZOP identifies mid-states by, for example, looking successively at each individual length of pipe in the plant, and postulating "too much flow" in this pipe, and then too little flow, flow in wrong direction, temperature too high, temperature too low, wrong substance in this pipe, etc. From each such mid-state the application of HAZOP generates a downstream tree by asking "What are the consequences of this mid-state?" The incoming tree is generated by asking "How might this condition come about?"

5.4. A Generalization of HAZOP

As we did with FMEA, we can also generalize the HAZOP thought process in an interesting way, with the aid of the concept depicted in Figure 18. In this figure the mission is again divided up into a number of "phases," which might, for example, be stages in a manufacturing process. In each phase, certain functions are carried out, as specified by S_0.

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If all the functions in each phase are accomplished successfully, then the mission, by definition, succeeds. Therefore, if we define the mid-state $MS_{i,j}$ to mean "function i fails during phase j," then the set of the $MS_{i,j}$ forms a complete and finite set of mid-states. If we draw complete incoming and outgoing trees to each, we then have a complete set of scenarios.

MISSION PHASES

FUNCTIONS

COMPLETENESS PRINCIPLE:
ALL FUNCTIONS, ALL PHASES SUCCEED ⇒ MISSION SUCCESS
MISSION FAILURE ⇒ SOME FUNCTION FAILS IN SOME PHASE
(⇒ - means "implies")
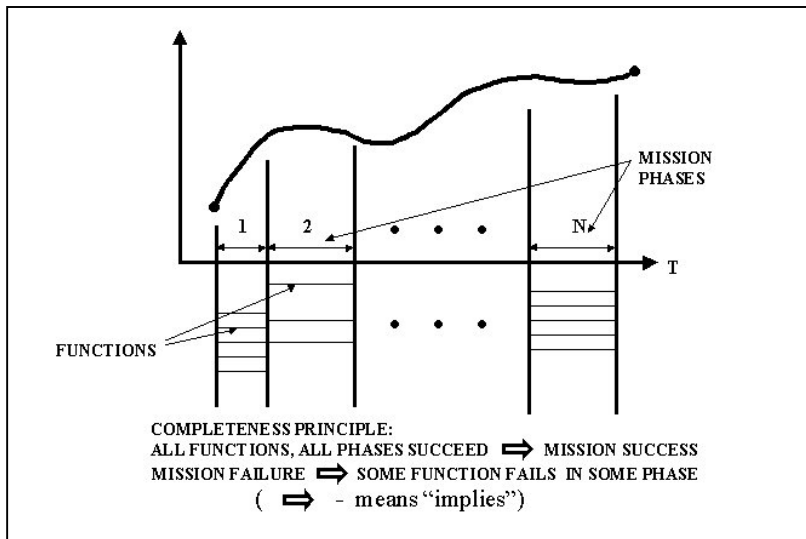
Figure 18. A Generalization of HAZOP

An idea of particular interest here is to generalize the HAZOP notion of "too much flow," or "too much heat," etc. to the notion of *function*. Thus we might ask, with respect to function i during phase j, "What would happen if we have too much function here?" What about too little function? Or the wrong function, or the right function but too early, or too late, or in the wrong direction, etc.?

This way of asking questions brings to mind, among other incidents, the sinking and capsizing accidents that have occurred in seagoing ferries (with considerable loss of life) when the bow doors were not closed completely. One is prompted to wonder: if the designers of those ferries had asked themselves questions such as these, would it not have been a simple matter to ensure that the boat was unable to leave the dock unless the doors are securely shut?

The point here is that in doing risk assessment on any system, process, or operation, *any* new way of asking questions is valuable because it "stretches" our brains, forcing us to look at our system (or process, etc.) in a new way, thus yielding an awareness of scenarios that we would not otherwise have thought of.

This brings us to AFD, which is not only a new way of asking questions, but an entirely new approach to the task of finding risk scenarios. Simply the fact that it is *different* makes it valuable. In addition, AFD is especially useful in identifying the class of scenarios having to do with human error, neglect, etc., and with deliberate human actions such as terrorism, sabotage, competition, and combat.

Chapter 2
AFD-1: Failure Analysis

1. AFD-1 and AFD-2

We have now established enough background to discuss what AFD is and what it adds to the arsenal of scenario-finding methods. We first note that AFD has two broad applications, which we will call AFD-1 and AFD-2. AFD-1 applies to finding the cause of a failure that has already occurred. In this application it would also be called *failure analysis*. AFD-2 is the application of AFD to identifying possible failures that have not yet occurred. This is called *failure prediction*.

To both of these important applications, AFD applies the following:

- Changing our attitude toward failure. People usually focus on learning about and explaining the failures that have happened before, in order to prevent them in the future. This is good, but not sufficient, for the reason that one cannot prepare for types of failures that have not happened previously. AFD-2 adds to this "reactive" approach an aggressive, pro-active one: to *predict* the failure you should *invent* it.

- Whereas QRA asks the question "What can go wrong?" with my system, plan, or operation, AFD-2 asks the question "If I wanted to make something go wrong, how could I do it in the most effective way?"

- Whereas traditional failure analysis asks the question "How did this failure happen?" AFD-1 asks "If I wanted to create this particular failure, how could I do it?"

- The concept of *resources*: For any failure or drawback to occur, all the necessary components must be present within the system or its nearby environment.

- Any failure or drawback, once revealed, can be prevented, eliminated or – at a minimum – reduced, with help of I-TRIZ tools.

In the language of the Theory of Scenario Structuring, AFD-1 starts with a given end state or mid-state, (i.e., the failure that has actually happened) and seeks to determine the actual scenario that led to that end or mid-state. AFD-2 seeks to envision all the possible end states, mid-states, and IEs, and all the possible scenarios leading to and from these states. Thus we see that AFD-2 incorporates multiple, repeated applications of AFD-1, and for this reason is necessarily much more complicated. In fact, AFD-2 is a process for finding the complete set of scenarios S_i, as described in section 2.1 of Chapter 1. And as such, it is often a laborious process. The challenge will be to minimize the labor, and to master (i.e., bring order to) this complexity. Our motivation for persevering in the face of this challenge is, of course, our overriding intention to:

"Find the failures – before they find us!"

and our recognition that those failure scenarios which escape our scrutiny and find us first, often cause great pain as well as loss of life, treasure, and reputation.

2. The AFD-1 Template

To aid the user in applying AFD-1, the structure of the associated "thought process" is laid out in the form of a template (Appendix 1). This thought process is extremely powerful and well worth incorporating into one's mental arsenal. For this reason, we will now walk the reader through the five-step template for the purpose of providing an overview of the process. We will then present two examples.

STEP 1. FORMULATE THE ORIGINAL PROBLEM

The first step in the template is to formulate what we call the *original problem*. This includes naming the system, stating its purpose, and describing the failure that has occurred.

STEP 2. IDENTIFY THE SUCCESS SCENARIO

In Step 2 we further familiarize ourselves with the system by briefly describing its *success scenario*, i.e., the phases of operation and the results that are intended to be accomplished in each phase.

STEP 3. LOCALIZE THE FAILURE

Step 3 then *localizes the failure* by identifying the phase and or/part of the system in which it occurred. The main purpose of localizing the failure is to reduce the area of analysis by identifying the system's functions (operations) that cannot possibly cause the failure, and remove them from further consideration. For this purpose we try to identify the *Last Event* – i.e., the system function (or operation) during which, or immediately after which, the failure appears.

STEP 4. FORMULATE AND AMPLIFY THE INVERTED PROBLEM

In Step 4.1 we reformulate the *original problem* into an *inverted problem* by restating it as the problem of *creating the observed failure*. Thus, instead of guessing about the possible causes of the given failure, AFD-1 "inverts" the problem by formulating it as follows:

> **It is necessary to produce the specific phenomenon (the observed failure) under the conditions that initiated and/or accompanied the observed failure.**

This rephrasing of the problem converts it into an *inventive problem* – one in which we ask "How can I . . . do something . . . make something happen?" (See Figure 19.)

In step 4.2, AFD recommends that we not only invert the question, but that we dramatically "amplify" or "exaggerate" the inverted formulation. For example:

- When a particular failure takes place at a point, or in some part of the surface or volume, the amplified formulation of the problem should include expressions such as: " . . . over the entire surface," or " . . . throughout the entire volume."

- When the failure occurs rarely or from time to time, we should amplify the formulation using expressions such as "repeatedly," or "constantly."
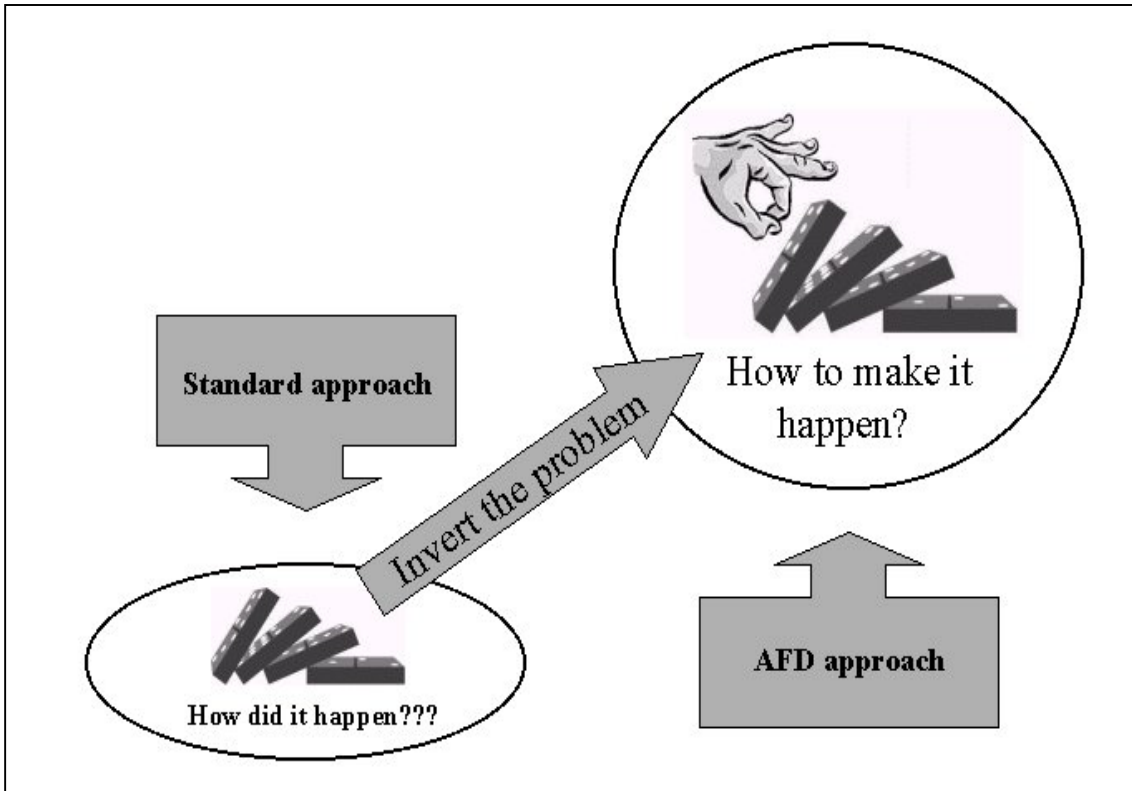
Figure 19. Inverting the Problem

One value of *amplification* is that it makes the problem more vivid and stimulates our inventive thinking.

Another, perhaps even more important result of amplification: the problem formulation is now similar to one describing a problem of *production,* as in, "How can I produce (or create) something?" (See Figure 20.) This resemblance is especially helpful during the next step of the AFD process.

STEP 5. SEARCH FOR SOLUTIONS

After the problem has been inverted and amplified, it reads the following way:

It is necessary to produce the amplified failure . . .

Our attention has now been diverted from "things that can happen" to "things that can be produced." And now the search for solutions begins.

Step 5.1 Search for Apparent or Obvious Solutions

The first recommendation in searching for solutions is the following:

Identify the areas of science, engineering, or even everyday life, where this same phenomenon is *intentionally created*.

This statement directs us to a different field of knowledge – namely, *methods of production*. And this is important not simply because it constitutes a different approach to failure analysis, but because it directs us to a field that is, traditionally, rich with information.
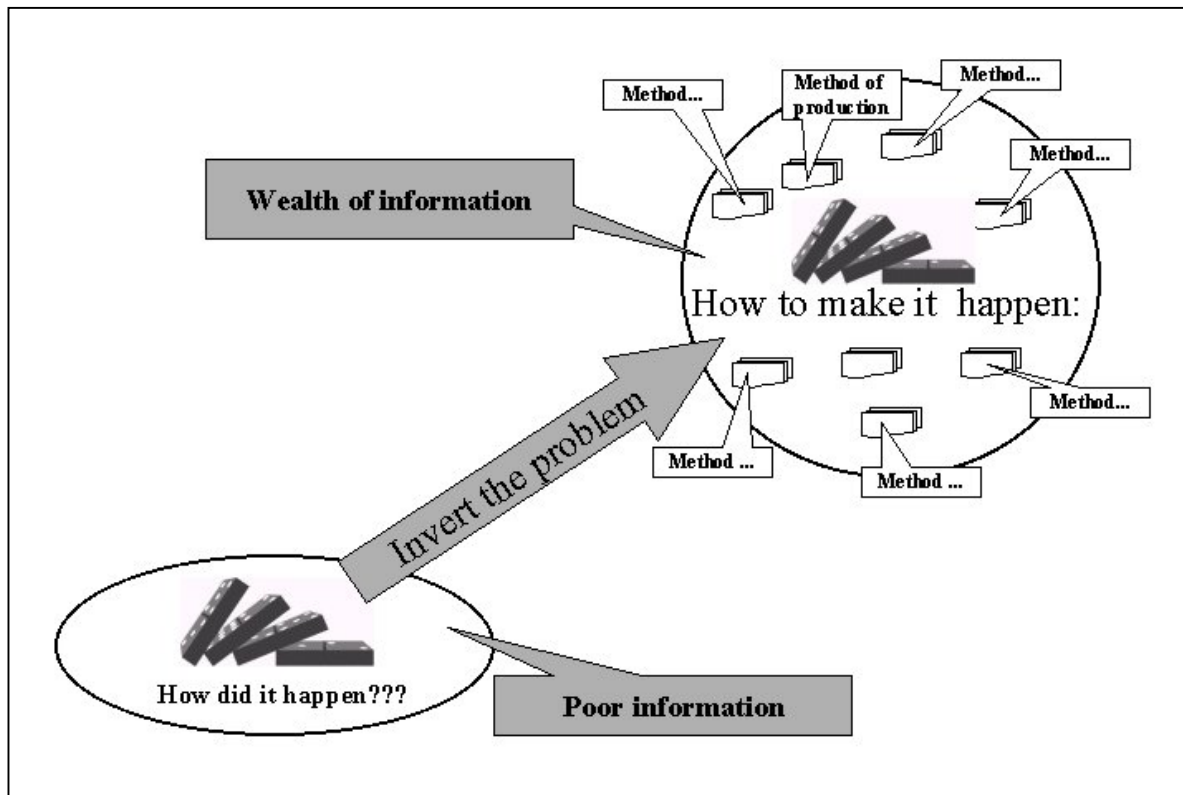
Figure 20. From "How Does It Happen?" to "How Can it be Produced?"

Once we have the amplified problem formulation, we can go to the patent library, conduct an Internet search, utilize the I-TRIZ Innovation Guide, or simply formulate direct questions to Subject Matter Experts in the corresponding technology. By utilizing these new possibilities, we can usually obtain at least several well known, "standard" ways of producing the desired phenomenon.
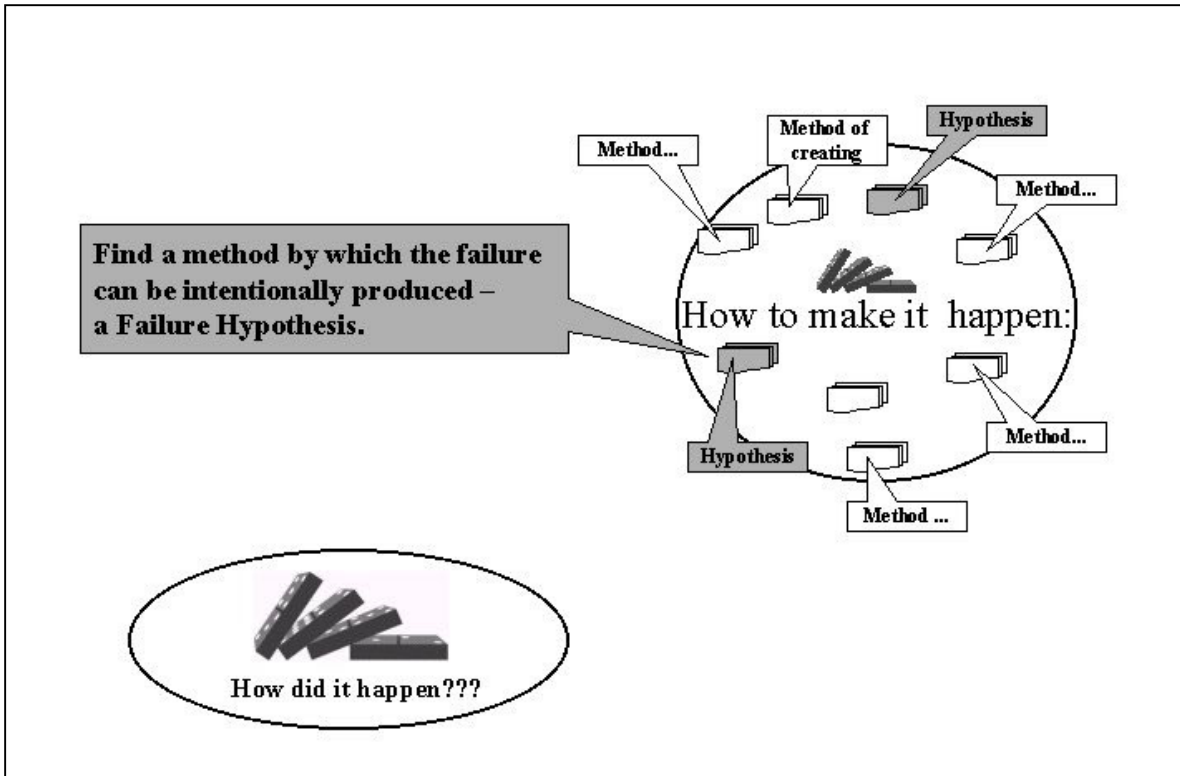
Figure 21 Finding Failure Hypotheses

Step 5.2. Identify Resources

This step follows from the recognition, in terms of the inverted problem, that:

> **Any of the identified methods for producing the desired phenomenon will require certain resources.**

The same notion, stated in terms of the original problem, is that:

> **For any failure or drawback to occur spontaneously, all the necessary components must be present within the system or its nearby environment.**

To search for necessary resources, one should do the following:
- Identify resources required for realization of a given phenomenon
- Find necessary resources in the system or its surroundings

For example, if our method for producing the phenomenon is to apply acid to our object, then to implement this method, acid must be available as a resource (either within the system or its environment) together with a means of applying it to the object.

Step 5.2, therefore, directs us to take a systematic inventory of the resources available within the system or its environment. The AFD software can be very helpful in carrying out this step by providing categorized lists of different types of resources, such as:

- ◆ Substance resources
  - Waste
  - Raw materials or unfinished products
  - System elements
  - Inexpensive substances
  - Substance flows
  - Substance properties

- ◆ Field resources
  - Fields (energy) in a system
  - Fields (energy) from the environment
  - Sources of fields
  - Fields of dissipation - energy waste

- ◆ Space resources
  - Occupy vacant space
  - Use another dimension
  - Arrange vertically
  - Use the reverse side
  - Nesting ("*matreshka*")
  - Travel through

- ◆ Time resources
  - Preliminary action
  - Partial preliminary action
  - Preliminary placement of an object
  - Create pauses
  - Eliminate idling
  - Concurrent operations
  - Group processing
  - Staggered processing
  - Use post-process time

- ◆ Informational resources
  - Fields of dissipation
  - Substance properties
  - Substance flows from a system
  - Substance/field flows passing through
  - Alterable properties of substances

- ◆ Functional resources
  - Functions of the system or its elements
  - Find an application for harmful functions
  - Super-effects (effects provided through the cooperative action of different parts of the system)

While taking this inventory, the solution to our problem might just leap out at us. We may see, in a flash, how an available resource, together with an identified standard method, can combine to produce the observed failure phenomenon. If this should happen, we have solved our problem. If not, we move on to:

Step 5.3. Utilization of Resources and Searching for Needed Effects

Since our identified standard methods did not work for us (a necessary resource is missing, for example), Step 5.3 directs us in the "creation" of the necessary resource from those resources that are available. Thus we might, for example, search for the less obvious, less well-known, physical, chemical, or biological "effects" that, together with the resources we have available, can create the failure phenomenon we are trying to produce. (If we need an acid, we can obtain it from existing components that can produce a particular chemical reaction).
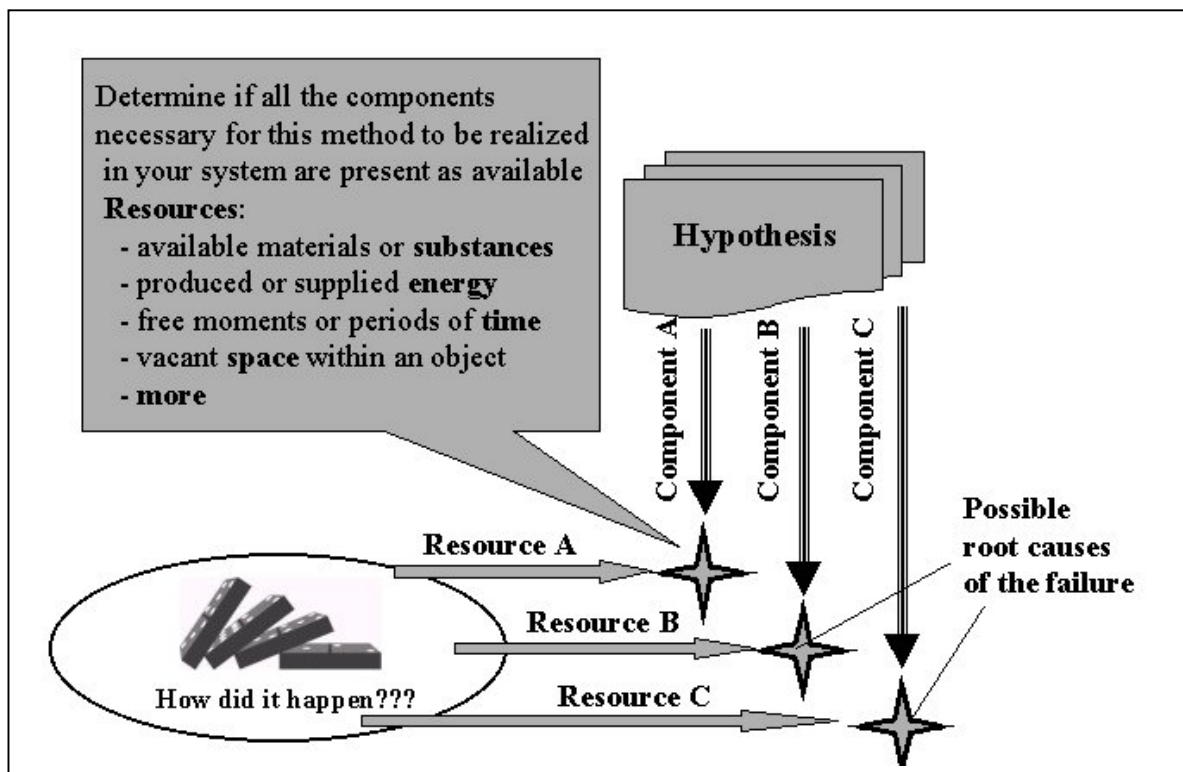
Figure 22. Utilization of Resources

In this search for needed effects, the I-TRIZ Innovation Guide software module can be very helpful, being an organized compendium of less well-known effects as well as the standard methods. If this search identifies an effect that will produce the desired failure phenomenon, and if the resources required for that production have been shown (in step 5.2) to be present, then the observed failure is explained and our problem is solved. If not, the template instructs us to move on to Step 5.4 . . .

Step 5.4. ARIZ (Algorithm for Inventing Problem Solving) for AFD

Note that what we have been doing, in steps 5.1, 5.2, and 5.3, is going back and forth in our thinking between the questions: "What physical effect or principle can create the desired failure?" "What resources do I need to implement this principle?" and "What resources do I have?" If we have not solved the problem completely by this time, we may have solved it "partially," i.e., we may have a general idea of how to solve it but do not yet see how to implement that idea. In this case we have what is called in I-TRIZ a *secondary problem*, the identification of which is made explicit in Step 5.4.2. To solve this problem we can apply any or all of the I-TRIZ tools: e.g., identifying the *ideal solution*, the Innovation Guide, targeting the technical and physical contradictions, applying the separation principles, Substance-Field Analysis, and/or the *operator method* [1,2,10]. The utilization of ARIZ is the best way to invent the most complicated and non-trivial failures that can be associated with the system. A simplified version of ARIZ for AFD consists of the following steps:

    1) Recap the Problem

    2) Formulate the Secondary Problem(s)

    3) Formulate the Ideal Solution of the Secondary Problem

    4) Search for ways to achieve the Ideal Solution

If, again, we find ourselves having only partially solved the secondary problem, then we are left with a *tertiary problem*, to which we can again apply the I-TRIZ methods.

STEP 6. FORMULATE HYPOTHESES AND DESIGN TESTS TO VERIFY THEM

In Step 6 of the AFD-1 template we formulate our hypothesis as to how the failure occurred and specify whatever tests are required to prove this hypothesis. Then, finally:

STEP 7. CORRECT THE FAILURE

In this step we specify ways to prevent the failure from occurring again.

3. Case Study for Failure Analysis: Applying the AFD-1 Template

The "Black Dots" Problem

This problem presented itself at a helicopter manufacturing plant. In the manufacture of aluminum longerons (the primary part in helicopter rotor blades), a certain type of defect – termed "black dots" – often appeared. The longeron is subjected to millions of loading cycles during its operational lifetime, and must be entirely free of defects. During the manufacturing process, the surface of the longeron (which looks like a long pipe of complex shape) is machined and then polished. After the final polishing operation, the longeron is sealed in a plastic bag and stored outside, under a roof, to await the next operation – electro-oxidation. Immediately after electro-oxidation, the black dots appear on the longeron surface. Under a microscope, these dots looked like miniature pinholes. This defect is extremely hazardous because the pinholes reduce the longeron's resistance to fatigue. Engineers had been unable to determine the cause of the black dots for many years. Eliminating the black dots must not cause degradation of useful functions, nor must new drawbacks be created.
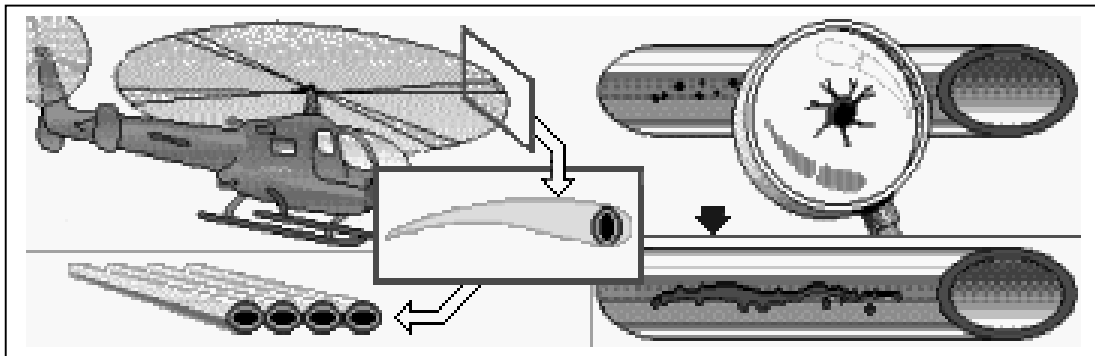
Figure 23. "Black Dots"

STEP 1. FORMULATE THE ORIGINAL PROBLEM

> **There is a system called** *the longeron or helicopter blade, which is a pipe of complex shape with polished and oxidized surfaces for providing the lifting force (when rotating)* **for** *a helicopter*.

STEP 2. IDENTIFY THE SUCCESS SCENARIO

OPERATIONS	RESULTS
1. Longeron pipe machining	Machined part with desired shape
2. Polishing outer surface of longeron	Outer surface prepared for coating
3. Sealing longeron in plastic bag	Longeron protected from atmosphere
4. Store under roof	Longeron held for next operation
5. Electro-oxidation	Longeron coated with aluminum oxide

STEP 3. LOCALIZE THE FAILURE

Immediately upon completion of electro-oxidation, the black dots are observed on the longeron surface. This does not happen to every longeron manufactured, but it happens often enough to be troublesome. This phenomenon is observed to occur more frequently during spring and fall seasons.

STEP 4. FORMULATE AND AMPLIFY THE INVERTED PROBLEM

Step 4.1. **It is necessary to produce** *black dots on the surface of the longeron* **under the conditions of** *the existing manufacturing process.*

Step 4.2. **It is necessary to make** *a piece of the longeron surface completely black* **under the conditions of** *the existing manufacturing process. Furthermore, it is necessary that this happen to every longeron manufactured.*

STEP 5. SEARCH FOR SOLUTIONS

Step 5.1. Search for Apparent or Obvious Solutions

The same phenomenon is intentionally created in the following areas:

As a result of an information search, using the Innovation Guide, and discussions with Subject Matter Experts, it was learned that this same phenomenon – blackening an aluminum surface – is intentionally realized in the manufacture of some aluminum consumer products. This is accomplished via a special and well-known process in which the aluminum surface is exposed to dilute hydrochloric acid and treated by electro-oxidation (i.e., connected to the positive pole of a d.c. source). Once this is known, we can identify a possible "mid-state" preceding the "end-state," namely the event: the surface is exposed to hydrochloric acid. Next, we look at the available resources to see if there are any that might be utilized for creating this mid-state or preceding event.

Step 5.2. Identify Resources

The resources (readily-available or derived) are:

a) Substances: aluminum metal, moisture, air, lubricant, coolant.

b) Fields: temperature changes, chemical potential

Step 5.3. Utilization of Resources and Searching for Needed Effects

There is no hydrochloric acid among the readily-available resources. How might this acid be derived from the resources that are available? Hydrochloric acid consists of hydrogen and chlorine. There is plenty of hydrogen (water component) around: moisture in the air, coolants, etc., and chlorine is present in tap water. It was confirmed that the coolant was tap-water based and was therefore, in effect, a dilute form of hydrochloric acid. Was it possible that drops of hydrochloric acid from the coolant could remain on the surface of the longeron? In fact, this hypothesis does not withstand further investigation. After machining (where the coolant is introduced), each longeron is polished so that no liquid remains on the surface. Thus we have a secondary problem: How can we "store" the water with the acid in the longeron?

Once again, we must look for resources. Since our objective is to create the dots, we must look for a way to "store" a certain amount of liquid (i.e., hydrochloric acid) somewhere. As was mentioned above, the longeron is a pipe During the machining process some water gets inside and stay there as small pools. Polishing, however, occurs only on the outside, and therefore hydrochloric acid can remain on the inside of the longerons. But the "dots" appear on the outside . . .

We now have another secondary problem: How can we move the acid from the inside to the outside? To solve this problem, we use ARIZ:

Step 5.4. ARIZ for AFD

5.4.1. *Recap the Problem:* The desired blackening can be produced through exposure to dilute hydrochloric acid (Figure 24). Dilute hydrochloric acid is present in the cooling water used during machining (Figure 25). But the drops of hydrochloric acid accumulate on the inside surface of the pipe, whereas we need them on the outside surface. This constitutes a secondary problem.

Figure 24. Exposure to Dilute Hydrochloric Acid

5.4.2. *Formulate the Secondary Problem:* Find a way to transport the acid drops from the inside of the pipe to the outside.

5.4.3. *Formulate the Ideal Solution of the Secondary Problem:* The ideal solution of the secondary problem would be that the drops of hydrochloric acid "move themselves" to the outside surface, without any additional system changes, and after the pipe has been carefully wiped.

5.4.4. *Search for Ways to Achieve the Ideal Solution:* According to the Innovation Guide, one way to transport a liquid is through evaporation. Therefore, it is possible that the drops can be transported if the water-acid solution inside the pipe vaporizes and then condenses on the pipe's outer surface. Thus, evaporation followed by
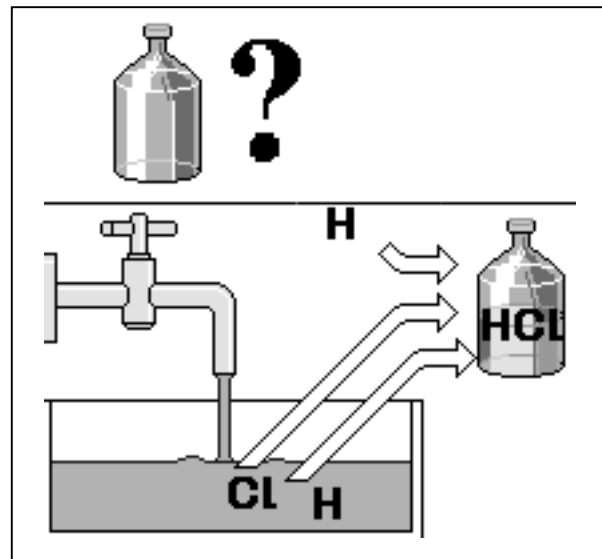
Figure 25. HCl Present in the Cooling Water

condensation is an effect that would accomplish our purpose. However, to implement this effect requires a resource; namely, a temperature cycling. Do we have this resource?

During manufacture of the blades there is no temperature variation, but when the blades are packed in plastic bags and stored outside the building they are subject to the cyclical variations of temperature between day and night. So, we have our resource (Figure 26).
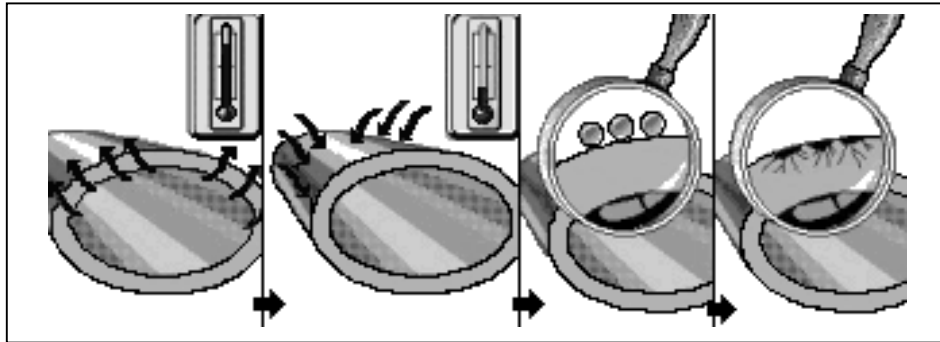
Figure 26. Condensation and Evaporation of HCl

STEP 6. FORMULATE HYPOTHESES AND DESIGN TESTS TO VERIFY THEM

Hypothesis: When the outside temperature changes (e.g., it is hot during the day and cool at night) the water-acid solution evaporates from inside the pipe and condenses on the outside surface. In this way small drops of the dilute hydrochloric acid have already prepared places for the development of the black dots after electro-oxidation.

First, this hypothesis was proved by statistics – it was known these variations were strongest during spring and fall (when the phenomenon has been most pronounced). Now it was understood why: there is no evaporation from inside when it is cold, and there is no condensation outside when it is. A simple test confirmed this hypothesis.

STEP 7. CORRECT THE FAILURE

After this hypothesis was confirmed, creating a method for preventing the black dots was a simple matter. Not only should the outside surface of the longeron be wiped, but the inside should be wiped as well. Placing a small package of silica gel in the bag will further ensure dryness. (See Figure 27.)
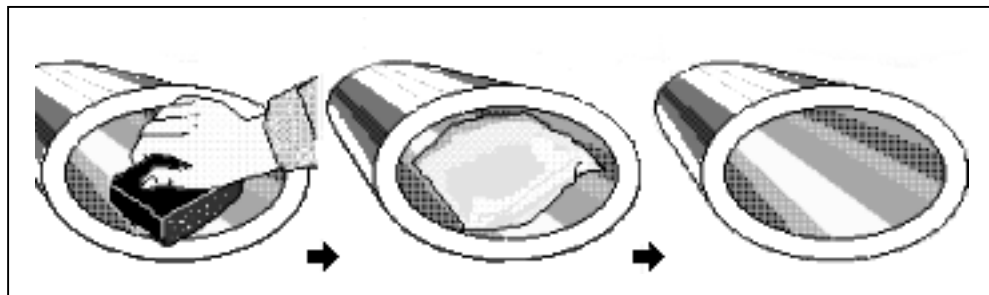
Figure 27. Method for Preventing Black Dots

4. The Black Dots Case Study Viewed as an Application of the Principle of Solution by Abstraction

It is instructive to view the solution process used in this case study in terms of the Solution by Abstraction Principle portrayed in Figure 6 of reference [2] and repeated here as Figure 28.

In this figure we start in the lower-left corner with our specific inventive problem. The next
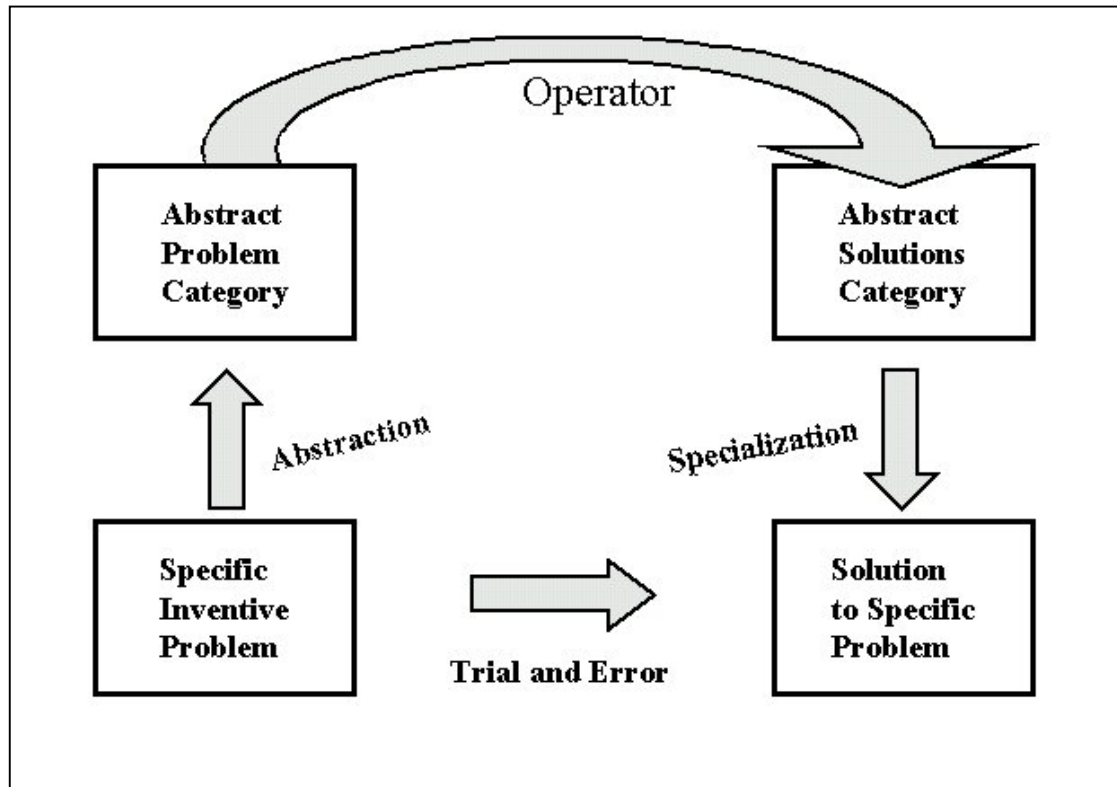
Figure 28. Principle of Solution by Abstraction
(Applied to Inventive Problems)

step is to "abstract" or "generalize" our specific problem and thus recognize it as a member of a category of inventive problems. Next, moving to the right, we find (using the I-TRIZ tools) an appropriate *operator* that solves the abstract problem category. The final step is to "specialize" the abstract solution back down to the solution of our specific problem, as shown.

Figure 29 shows this abstraction principle applied three times, successively, to the Black Dots problem. At the left of the figure we see our specific problem: Create Black Dots (on our heli-copter blades, or longerons). Moving up, we abstract this to the general problem of Blackening Aluminum. The operator for doing this, suggested by the Innovation Guide, is to apply HCl along with electro-oxidation – this is the abstract solution for the abstract problem. To implement this solution we need three things, as shown by the "and" gate: HCl, electro-oxidation, and application of the HCl to the surface of the longeron. The HCl and electro-oxidation are already present as resources in our specific problem – however, application of the HCl to the longeron surface remains as a secondary problem.

Applying the abstraction principle to this secondary problem, on the right side of Figure 29,
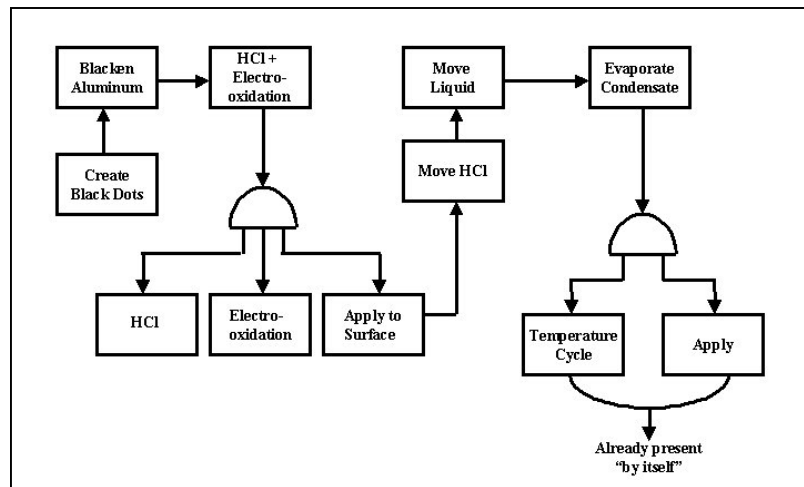
Figure 29. Solution Process for Black Dots Problem

we recognize the following problem: how to store the HCl with the longeron. This problem was solved with a simple investigation of resources, whereby it was determined that the inside surface of the longeron was adequate to store the liquid.

Applying the abstraction principle to this secondary problem, on the right side of Figure 29, we recognize the problem of moving HCl as a special case of the general problem of moving liquid. One of the ways to solve this general problem, suggested by the Innovation Guide, is to use evaporation and condensation. To implement this solution we need to apply a temperature cycle to the blades. In our particular case, this "resource" is already present in the form of the daily temperature cycle that acts upon the blades as they are stored in the yard of the plant. So nothing more needs to be done and we have our explanation of the observed failure.

5. The Black Dots Solution Viewed as an Incoming Scenario Tree

Figure 30 portrays the solution as an incoming scenario tree to the end state "black dots." One way to reach this end state is by exposing the longeron to HCl and electro-oxidation. In this case, exposure requires the storage and transport of HCl to the longeron surface; one way of doing this is through evaporation/condensation.
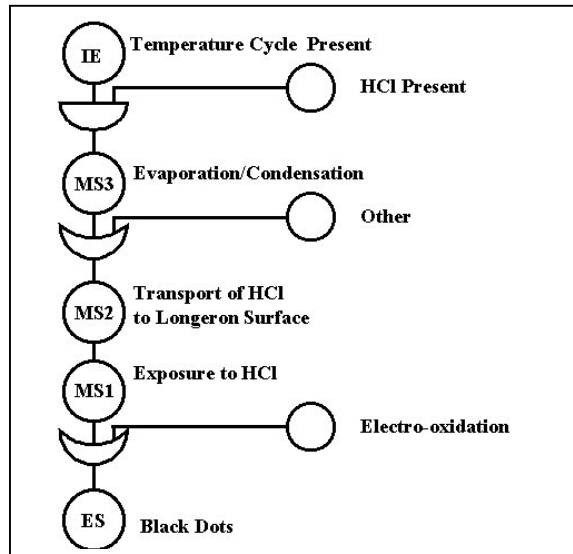
Figure 30. Incoming Scenario Tree
for the "Black Dots" Problem

6. Another AFD-1 Example

"Poisoned Whiskey" Problem

During salvage operations on a sunken ship that had been used to transport fertilizer, a diver discovered some unopened whiskey bottles. He took one and, later that night, he and a friend drank the whiskey, after which they both were poisoned. How can this be explained?

STEP 1. FORMULATE THE ORIGINAL PROBLEM

> **There is system**, a properly-corked whiskey bottle that has been submerged deep in the ocean for a long period of time on a ship that had been transporting fertilizer. After the bottle was recovered, whiskey was drunk from it, after which **an undesired effect occurred:** namely, poisoning of the drinkers. **It is necessary to find the cause of this phenomenon.**

STEP 2. IDENTIFY THE SUCCESS SCENARIO, S_0

PHASES	RESULTS
1. Bottle on ship prior to sinking	Bottle well corked
2. Bottle on bottom after sinking	Bottle remains sealed from sea water
3. Bottle recovered to surface	Bottle remains well corked
4. Bottle opened, whiskey drunk	No ill effects

STEP 3. LOCALIZE THE FAILURE

First we must verify that the cause of the poisoning was the whiskey, and not, for example, the caviar that was consumed at about the same time. Assuming this verification has taken place, we are at mid-state MS1 in Figure 31. We now ask: When did the whiskey become poisoned?

Before sinking with the ship, the bottle was presumably well corked and the liquid inside was presumably non-poisonous (other that the alcohol itself). When the bottle was retrieved it also appeared to be well corked, yet when the whiskey is consumed, the divers become poisoned. Therefore, poison must have entered the bottle during its time on the ocean floor.

STEP 4. FORMULATE AND AMPLIFY THE INVERTED PROBLEM

Step 4.1. **It is necessary to produce** *the undesired effect of poisoning of the whiskey* **under the conditions of** *deep submergence of the bottle for a long period of time in the vicinity of a load of submerged fertilizer, along with no evident deterioration of the cork*.
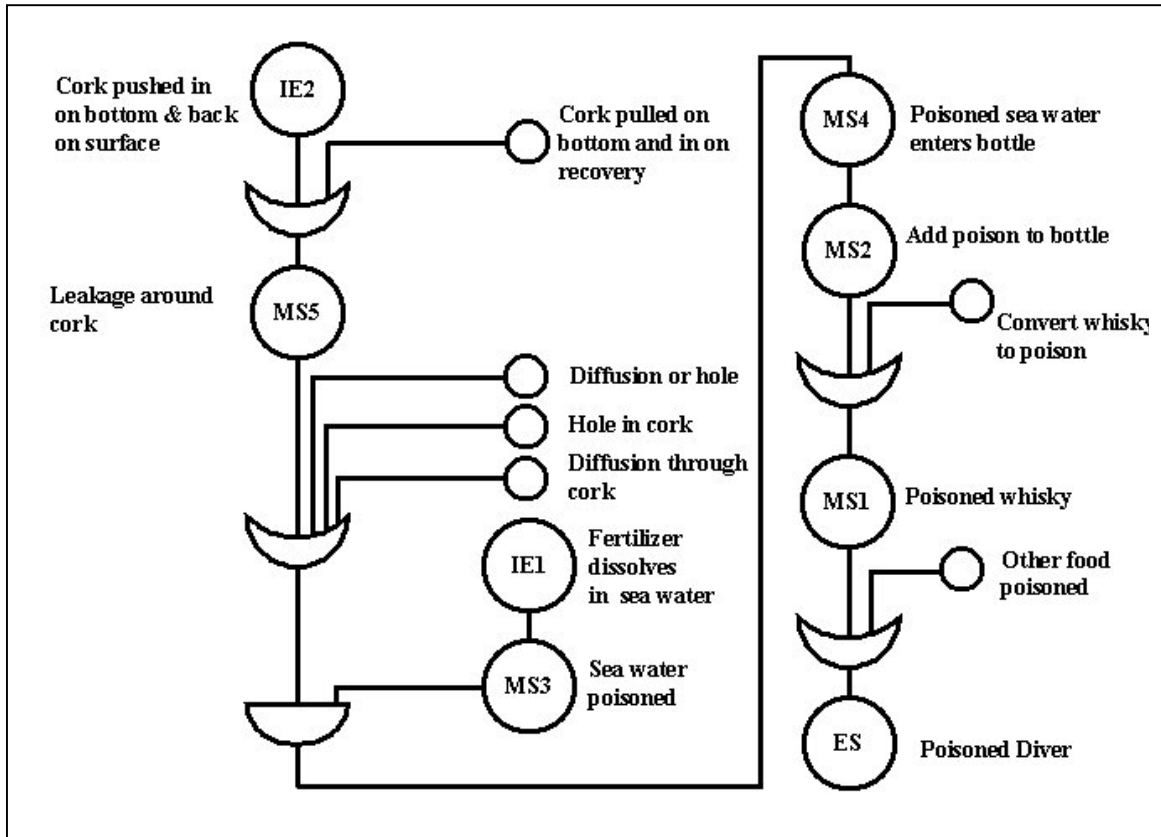
Figure 31. Principle of Solution by Abstraction
(Applied to Inventive Problems)

Step 4.2. **It is necessary to** *ensure that the whiskey in the bottle will become poisonous each and every time* **under the conditions of** *the bottle being properly corked and submerged deep in the ocean for a long period of time in the vicinity of fertilizer.*

STEP 5. SEARCH FOR SOLUTION

Step 5.1. Search for Apparent or Obvious Solutions

There are only two possible ways to poison the whiskey. We can:

> (1) Add poison to the liquid in the bottle,
>
> or
>
> (2) Convert the substance already in the bottle to a poisonous form.

(This branch is reflected in the "or" gate to mid-state 1 in Figure 31). In the discussion that follows we shall pursue possibility (1) and leave possibility (2) for later consideration, if necessary.*

---
* Possibility (2) is not inconceivable. For example, there might be microorganisms in the bottle, which, given the conditions and time duration involved, might produce poison as a result of their natural metabolic processes.

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Possibility (1) requires us to do two things, as shown by the "and" gate to MS2. We must create poison in the seawater surrounding the bottle, and we must get some of this poison into the bottle. The obvious candidate for the poison is the fertilizer, which dissolves readily in seawater. The question then becomes: How can we get the poison into the bottle? Obvious possibilities here are leakage through a hole in the cork or diffusion through the cork itself.[**]

Step 5.2. Identify Resources

♦ Substance resources of the system are:
  - Bottle, cork, whiskey, fertilizer, seawater

♦ The field resources are:
  - Pressure of the sea water
  - Pressure inside the bottle
  - Chemical gradient from fertilizer dissolved in the seawater but not in the whiskey

♦ Functional resources are:
  - Poisonous nature (to humans) of fertilizer
  - Ready solubility of fertilizer in seawater

♦ Time resources:
  - Time between bottling of whiskey and sinking of ship
  - Time spent in deep water after sinking
  - Time between taking of bottle and drinking by diver
  - Time between drinking and symptoms of poisoning

♦ Space resources
  - Space in the ship where bottle was
  - Space around bottle
  - Space inside the bottle and bottle neck

Step 5.3. Utilization of Resources and Searching for Needed Effects

Ways to produce the desired phenomenon (penetration of seawater into the bottle) are:

a) diffusion through the cork

b) leakage through a small opening in the cork

c) diffusion or leakage through a small hole in the glass itself

d) leakage around the cork, i.e., between the cork and the bottle

Getting the poison into the bottle through a hole in the cork seems like an obvious cause; however, examination of the cork did not reveal any holes. Diffusion is also obvious, but seems unlikely. Diffusion through the glass seems extremely unlikely, and, indeed, examination of the bottle showed no pinholes or cracks in the glass. The remaining possibility is leakage around the cork, but since the cork appeared to be properly seated, this also seems unlikely.

[**] Another possibility is that a venomous sea animal injects poison through the cork. We considered this as very unlikely, however, and thus it is omitted from the diagram.

Step 5.4. ARIZ for AFD (Search for a New Solution)

5.4.1. Recap the problem (at the current level of abstraction): The problem here is to cause seawater, which is poisoned with dissolved fertilizer, penetrate into the bottle via leakage around the cork during the long, deep submergence.

5.4.2. Formulate the secondary problem: The secondary problem is that upon examination at the surface the cork appeared to be properly seated so that leakage around it seem highly unlikely

5.4.3. Formulate the Ideal Solution of the Secondary Problem: The ideal solution is that the seawater/poison flow into the bottle "itself" without damaging the bottle cork.

5.4.4. Search for Ways to Achieve the Ideal Solution:
- Pull the cork out of the bottle, or pull it part way out.
- Push the cork into the bottle, or part way. (This is an example of the I-TRIZ operator *inversion*.)

5.4.5. Identify the Barriers to Providing the Ideal Solution: There seems to be no mechanism for pulling the cork out. There is, however, a resource available for pushing the cork in, namely, the pressure of the seawater at the bottom is much greater then that in the bottle.

5.4.6. Identify the Contradiction: The bottle seems to be corked properly, and yet must be corked improperly because it allowed liquid to flow into the bottle.

5.4.7. Apply the I-TRIZ Separation Principles: This contradiction can be resolved by the principle of *Separation in Time*. The bottle was corked properly before and after recovery from the bottom, but while it was on the bottom it was corked improperly and allowed leakage into it. What difference exists between the conditions on the sea bottom and on the surface that could be responsible for the change in the cork's performance? The major difference is pressure. Aha! We have a new solution! This leads us to form the following hypothesis:

STEP 6. FORMULATE HYPOTHESES AND DESIGN TESTS TO VERIFY THEM

High water pressure on the sea bottom pushes the cork down into the bottle neck a little, allowing sea water (containing dissolved fertilizer), to seep in around the cork. When the bottle is raised, the higher pressure inside the bottle forces the cork back up into place.

This hypothesis can be checked by examining the chemical composition of the sides of the cork. If there are fertilizer molecules present there, it proves that the hypothesis is correct. Another way to verify the hypothesis is to place a similar bottle under the same pressure with liquid containing radioactive or luminophorous markers, then check for the presence of the markers in the bottles.

The diffusion hypothesis can be checked by examining the center of the cork. The presence of fertilizer molecules there would support this hypothesis.

STEP 7. CORRECT THE FAILURE

The ways to prevent or correct this kind of failure are:
- Avoid sinking the ship.
- In recognition of the fact that the ship's cargo is poisonous and soluble, alert divers and everyone else involved not to ingest anything from the vicinity of the sunken ship, including fish and other sea life.

Chapter 3
AFD-2: Failure Prediction

As we stated above, Failure Prediction has much in common with Failure Analysis. The main difference is that the Failure Prediction question, since it seeks to find "all," or at least "all of the important" failures, is more complicated and leads to a profusion of IEs, MSs, HESs, and S_is.

A major problem in Failure Prediction, then, is the "bookkeeping" required to effectively manage this profusion. For this purpose, the Failure Prediction template urges the user to adopt a numbering scheme for the various events, and to draw scenario trees as he/she works.

1. The AFD-2 Template

The template for AFD-2 is given in Appendix 2. As with AFD-1, Step 1 of the AFD-2 template is a formulation of the *original problem*. The difference is that for AFD-2 the original problem is to find *all* (or all of the important) possible failures in the system at hand.

Step 2 of the template is the same as for AFD-1, namely, a description of the *success scenario*, S_0, of the system in terms of the phases of the process and the results achieved at the end of each phase.

Step 3 formulates the *inverted problem*, which is to create or produce all the possible failures that can occur within, or as a result of, the system being studied.

In Step 4, we write down all the obvious possible failures of the system that we can readily think of. To help us in our thinking we can focus separately on the possible *initiating events* (IEs), *harmful end states* (HESs), and *mid-states* (MSs). We then combine these into complete risk scenarios (S_is) and organize these scenarios into *scenario trees* of appropriate types, as described in Sections 4 and 5 of Chapter 1.

We then move beyond the obvious, as Step 5 asks us to conduct a survey of the resources available in or around our system that might be useful in creating failure scenarios. To aid us in this endeavor, the template identifies categories of resources that might be present. The AFD software also helps us by offering checklists of specific resources that might be present within each category.

As we become aware of the resources present in or near our system, failure modes and failure scenarios might occur to us that we have not previously thought of. These scenarios should be labeled and numbered appropriately and added to our scenario trees.

For still more ideas on potential failure scenarios, Step 6 of the template suggests that we study another set of checklists (incorporated in the AFD software and included here as Appendix 1) to look for items that might be associated with additional IEs, MSs, and HESs. And again, any scenarios that arise should be numbered and included in the trees.

In Step 7, the template shifts to an "incoming tree" point-of-view with respect to the important HESs and MSs that have been identified, and asks us to consider additional ways by which these events can be created. For this purpose, the software employs the use of the Innovation Guide and ARIZ (as in the template for Failure Analysis).

Having now found the HESs and failure scenarios, the AFD-2 template suggests ways to "worsen" them – by intensifying them or keeping them hidden from human operators until they become appropriately severe. For this purpose, we are again directed to the AFD checklists included in Appendix 2.

Finally, the template asks us to "clean up" and organize our scenario trees so that they are understandable. These trees now constitute the set of S_is for our problem.

If the user now desires to eliminate some of these failure scenarios, the template recommends doing so by way of the I-TRIZ *operators*.

An example of the application of Failure Prediction (via the AFD-2 template) to a fender manufacturing process is presented in Appendix 3.

Chapter 4
Further Notes and Commentaries on the AFD Approach

1. What Makes AFD Work? A Discussion of the "Inversion" Concept

As we have noted in Chapter 2, Section 1, and as we have seen in both the AFD-1 and AFD-2 templates, a key step in the AFD method is to "invert" the original problem. Thus, whereas in ordinary Failure Analysis we would ask: "Why did the observed failure occur?" in AFD-1 we ask: "How can I create such a failure?" Similarly, in ordinary Risk Analysis we would ask: "What can go wrong with my process or operation?", whereas in AFD-2 we ask "How can I make things go wrong?"

An obvious value of this rephrasing of the problem is that it converts the problem into an *inventive problem* – i.e., the problem becomes "How can I . . . do something . . . make something happen?" This conversion makes available the entire I-TRIZ inventive apparatus, including the I-TRIZ knowledge base (constituted in AFD as an extensive set of checklists), and the I-TRIZ analytical methods, represented by ARIZ (from the traditional or so-called classical TRIZ), and the more recent *operator method* developed by Zlotin and Zusman.

To anyone familiar with the power of the I-TRIZ apparatus, making it available is more than enough to justify a rephrasing of the question. But there is more: There are two additional, more subtle values to this rephrasing or inversion, which we will discuss below:

1.1 The Phenomenon of Denial

We humans are subject to a psychological phenomenon called *denial*, in which we resist thinking about unpleasant things. We might say, for example, "It can't happen here," "Things will turn out all right," "It has never happened before," etc. When we are in this frame of mind we will tend not to hear bad news – indeed, we might even "shoot the messenger" instead. We will refuse to look at the evidence, and, if we do, refuse to believe what it tells us. The presence of the denial phenomenon is clearly seen in the historical evidence of various disasters, accidents, and failures.

The necessity of countering the denial phenomenon is one of the main reasons for quantifying the likelihood and consequences of failure scenarios. It is also a major reason for the *evidence-based approach*. The more the evidence is written down explicitly, and the more the inferences are drawn overtly and quantitatively via Bayes theorem, the harder it is for us to ignore what we don't want to see or hear. (Harder, but not impossible!) Of course, some of us will continue to believe what we want to believe in spite of overwhelming evidence.

The denial phenomenon is also to be blamed for the shortage of information about the failure within a system or its close environment – nobody is eager to share this kind of information.

There is reason to think that the inverted question may be useful in counteracting the denial machinery. For when we ask ourselves the QRA question "What can go wrong?" with our plan or operation, our minds become defensive and the denial phenomenon kicks in to negate and minimize the possibility of anything going wrong with our system or plan. But when we ask the inverted question: "How can I make something go wrong?" we put our

attention on the offensive side of the game. Our mind's payoff now comes from finding possible failures, and thus we actively engage our creative faculties to that end.

1.2 The "Production" Effect

In response to the question, "What can go wrong?" with our system or operation, we would naturally like to look in the available literature to find records of the failures that have occurred throughout the history of similar systems and operations. Unfortunately, however, the recorded database associated with failures is relatively meager. People, understandably, are not always willing to document (even less so to publicize) failures. On the other hand, the database associated with "how to do something" is enormously rich. A wealth of information exists on what mankind is traditionally proud of – how to produce some thing or create some effect. Thus, by inverting the problem we open the door to this vast body of information.
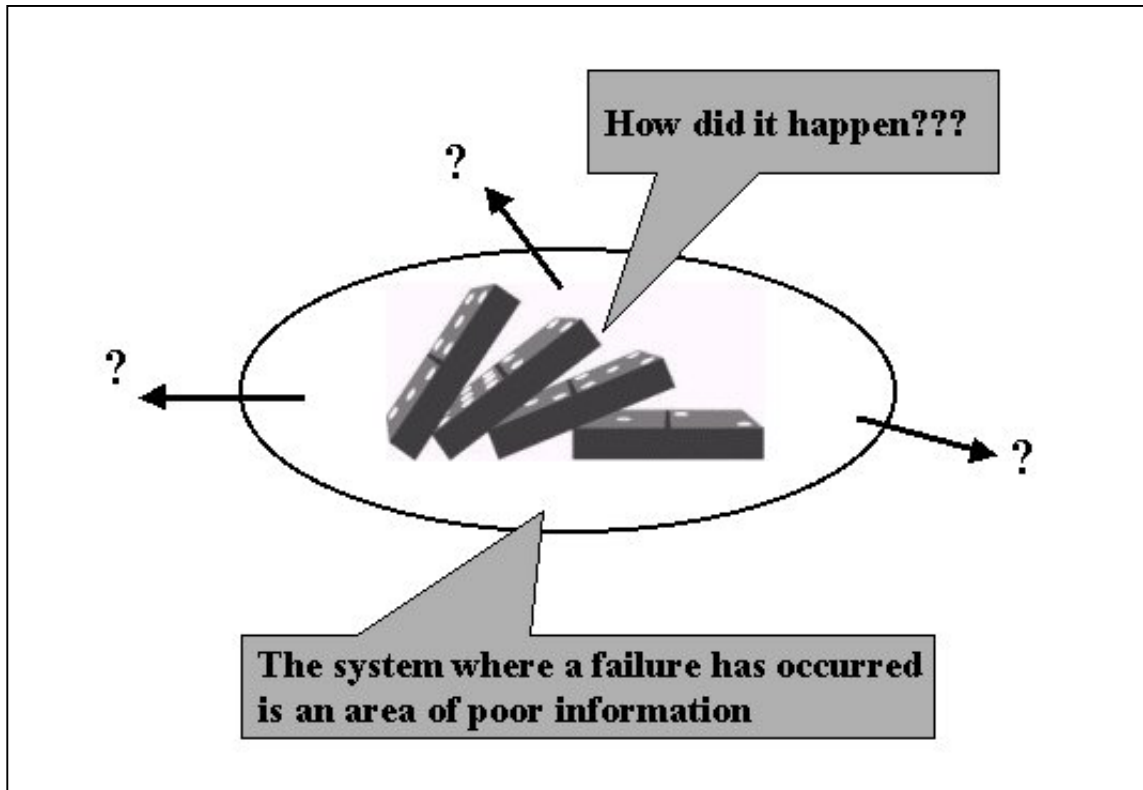
Figure 32. A Dearth of Information Exists Regarding Failures

2. Comments on the "Resources" Concept

One of the most powerful AFD tools is the concept of *Resources*, which is based on the following:

For any failure or drawback to occur spontaneously, all the necessary components must be present within the system or its nearby environment. If all those components are present, the failure will necessarily occur.

To solve the problem of revealing the root cause of a failure, it is therefore quite enough to:

1. Identify a well known, standard way of creating the observed phenomenon, and identify the required resources.

2. Verify that all the resources required to create that phenomenon are present or can be derived from what is present.

In the AFD process, resources are utilized in five different ways:

- Identifying the elements of the system that can directly contribute to causing the negative effect.

- Revealing the indirect influence(s) of available resources on the failure, through their interaction (in effect creating new resources from those already present).

- Answering the question: "What can help to destroy the system?" (This is the way that ideas are generated in Failure Prediction.)

- Assessing the likelihood of various hypothesized mechanisms of an observed failure. (If all the resources necessary for a failure mechanism are present, then it is 100% probable that that mechanism occurred. If all the necessary resources are not present in some fashion, then that mechanism could not have occurred).

- Selecting the most effective (or inexpensive) methods to prevent the repeat of an observed failure, or the occurrence of an identified possible new failure.

To elaborate on item 2, we note that we can invent new resource from those that are already available in the system or its closest environment. This is certainly a more complicated way of generating failure hypothesis, however it exactly reflects the main idea of resource utilization, while giving us a way to successfully identify the most tricky and subtle failure mechanisms.

Moreover, it is very effective to check the List of Resources several times during an analysis process. This provides the opportunity for new failure hypotheses at every new level of the system analysis.

There are at least six main methods for obtaining new resources without bringing in elements from outside the system.

1) The direct combination of available resources to provide a new result. In particular, the possibility of applying combinations of different fields, (e.g., electrical, magnetic, thermal, chemical, etc.) available in the system, or creating combinations of different substances by mixing, adjoining, etc.

2) Combining pre-selected properties of available resources to provide a required interaction between them.

3) Using physical effects that can be performed through system elements or elements available in the nearby environment.

4) Using chemical reactions and other chemical effects that can spontaneously occur via system elements or elements from the nearby environment.

5) Using geometric effects (i.e., specific properties of different lines and shapes).

6) Using "clever" technologies and other inventive tricks that can be performed via system elements or elements from the nearby environment.

As we can see, only the first and second methods can be realized easily by applying common sense and engineering knowledge. The other four ways actually require unique databases (which are included in the AFD software) that serve special purposes having to do with innovation.

3. The Checklists

Another contribution AFD-2 makes to the search for failure scenarios is the use of the *AFD knowledge base*, which consists of a set of nested checklists. These checklists essentially tabulate mankind's experience with failures in such a way that a user can go down the list item by item, considering how each might apply to his own system.

A good way to understand the AFD checklists is to return to Figure 8, in which we represented S_0 as a trajectory in the system state space, with time, t, as the parameter along that trajectory. If we wanted to make something go wrong, the first thing we might do is look along this trajectory (see Figure 18), to find those times where vulnerability is greatest. Towards this end, AFD offers the following two *time-oriented checklists*:

3.1. Time-Oriented Checklists

- **Checklist 3: Typical Stages in the Life Cycle of a Technical System**
- **Checklist 5: Typical Dangerous Periods in a System's Functioning**

In view of our present intention, the latter of the above checklists can be interpreted as "*stages or periods during which I can create failures.*"

Checklist 3 identifies the following stages:

3.1 Manufacturing

3.2 Testing

3.3 Packaging

3.4 Transportation

3.5 Sales and Purchasing

3.6 Installation

3.7 Maintenance

3.8 Repair

3.9 Disassembly and Salvaging

Each of these stages is associated with a sub-list of things that can go wrong during that stage. For example, Stage 3.7 (Maintenance) lists the following possibilities:

3.7.1   Violation of maintenance specifications

3.7.2   Inactivation of safety, backup, or redundant systems

3.7.3   Use of the system under conditions other than those for which it was designed, or for a purpose inconsistent with the systems original function

3.7.4   Undesirable influence on the system during maintenance

3.7.5   Incorrect or ill-timed service/maintenance

3.7.6   Dangers that can emerge during maintenance (i.e., dangers to maintenance personnel)

Checklist 5 lists the following dangerous periods:

5.1   Periods of departure from the usual routine

5.2   Periods of stressful change

5.3   Periods of change in personnel (e.g., shift changes)

5.4   Periods of high stress in an individual worker's personal life

5.5   Periods when tests and maintenance occur

5.6   Periods of crowding and vulnerability to panic

5.7   Periods when security is weak

Each of these items is further detailed with sub-lists and can be illustrated with real-life examples to make them more vivid.

3.2. Space-Oriented Checklists

After looking for vulnerable times, the next thing we might ask is "What regions in the state space are vulnerable to my efforts to create failures?" To help us answer this, AFD provides us with:

- **Checklist 4: Typical Weak and Dangerous Zones**

which includes the following:

4.1   Flow concentration zones

4.2   Zones subjected to the action of high-intensity fields

4.3   Conflict zones

4.4   "Bad history" zones

4.5   Zones containing junctions of different systems

4.6   Multi-function zones

4.7   Tool-workpiece contact zones

4.8   Zones of concentrated potential energy

and each of which is detailed further in the AFD software and, again, can be illustrated with examples of real-life failures.

3.3. "Types of Failure" Checklists

We might next ask ourselves "What types of failures could I create?" For suggestions, see

- **Checklist 2: Typical Harmful Impacts.**

In this checklist, various impacts are grouped by type, as follows:

Mechanical

Thermal

Chemical

Electrical

Magnetic

Biological

Electromagnetic

Information

Psychological/emotional.

AFD also provides:

- **Checklist 6: Typical Sources of High Danger**

which identifies opportunities for creating failures having very great impact. For still other points of view on what types of failures might be created, AFD provides:

- **Checklist 7: Typical Disturbances of Flows**

which suggests ways to interfere with the "flows" going on in the system, and:

- **Checklist 1: Typical Functional Failures**

which identifies functional failures that can be created at the system, device, component, or material level. This checklist also calls attention to the fact that we can interrupt a system's functioning at its "main-line" level, or at the level of the support systems on which the main-line systems depend.

3.4. Other Checklists

We might also ask ourselves: "What resources do I have available, at the various stages of S_0, with which to create failures?" To help answer this, the AFD software provides:

- **Checklist 8: Typical Resources Capable of Producing Harmful Impacts**

This constitutes an elaborate collection of possible resources. The notion of identifying available resources is a very important one in I-TRIZ, and often leads to the key creative concept in an inventive problem situation. Finally, we have the very important checklist:

- **Checklist 9: Patterns of Typical Failure Scenarios (including Human Errors)**

which identifies and abstracts the patterns of failures scenarios that have occurred, or could occur, in various industrial or non-industrial situations. These patterns are organized into

categories according to the situation, making it easy for the user to look for those patterns relevant to his/her project. This checklist contains a unique and promising idea, which we will discuss next.

3.5. Failure-Intensifying Checklists

As we know, the most dangerous harmful effects are those that can intensify with time, or those that "lie low" initially and then appear later with full force.

To generate this kind of failure hypotheses, two checklists were created. The first:

- **Checklist 10: Methods of Intensifying a Failure**

The suggestions provided in this checklist are as follows: To intensify a failure and prevent it from decreasing or escaping with time, try to:

1. Increase the failure with the help of the system itself
2. Break the system's natural compensatory processes
3. Eliminate the possibility of damage correction

- **Checklist 11: Ways of masking or hiding the failure**

To mask the failure, try to:

1. Cause the failure to appear in a place that is rarely monitored
2. Cause the failure to appear in a place that is difficult to access
3. Cause the failure to appear only when it is not observed
4. Divert the sensor's attention from the failure
5. Decrease the sensor's level of sensitivity

4. Comments on the Checklist Concept – Looking to the Future

Looking ahead to the future evolution of AFD, it becomes evident that the checklist idea has enormous potential. In particular, checklist 9 could be expanded so that it becomes a repository of worldwide experience on different types of mistakes, accidents and disasters that have occurred in various industries and operations. This information, codified, organized and illustrated with examples, pictures, diagrams, video clips, etc. could then be made available worldwide via the Internet. A young engineer who embarks on the design of a particular system could, with just a few keystrokes, call up the world's entire historical experience with systems of the same type as his/hers, together with lists of things to look out for, ways other designers have avoided such problems, etc.

Perusing the literature on accidents and disasters in various industries, it becomes clear that, oftentimes, similar incidents occur repeatedly, in different parts of the world, before they can be fully eliminated. This shows us that the transmission of knowledge as to the causes of these incidents is slow and inefficient. The checklists in AFD, together with the World Wide Web, offer us an opportunity to greatly improve the efficiency of this transmission.

5. Comments on the Innovation Guide

The Innovation Guide is dedicated to helping the user find a way to produce or apply the most popular technological (physical or chemical) effects. In general, it assists us in answering two kind of questions:

1) how to provide a required result ("I know what should be done, but don't know how")

2) how to apply an available effect (energy or process) in some other way than that which it presently performs

In the first case, we can open the Innovation Guide and select from the following ways of producing technological effects:

- Create a desired field or action/impact

- Produce a desired object or substance

- Transfer or remove an object or substance

- Find space in which to locate an object or action

- Find time for performing a desired action

In the second case, we select the ways of using technological effects:

- Apply a desired field or action/impact

The Innovation Guide serves three specific purposes in the AFD process:

1) finding a way to perform or produce a desired effect (Step 5 of the Failure Analysis template)

2) finding a way to achieve the ideal result when solving secondary problems (ARIZ for Failure Analysis or Failure Prediction)

3) generating new ways of producing harmful effects (Step 7 of the Failure Prediction template).

6. ARIZ (Algorithm for Inventive Problem Solving)

A short variant of ARIZ is included in the AFD software (see the attachment "ARIZ for Failure Analysis") for the following reasons:

1) as a very effective tool for resolving a conflict (contradiction) that can't be solved using any other tool

2) as a powerful I-TRIZ tool helpful for solving the most difficult of inventive problems

ARIZ serves the following purposes:

- To invent the most controversial and non-trivial failures that might possibly be connected with the system

- To help in those cases where we know what kind of phenomenon should be produced, but secondary problems or obstacles hinder it from being realized.

7. The Templates

To aid the user in applying the inverted question, AFD contains two templates. The Failure Analysis template (Appendix 1) is used to apply the AFD question to a specific identified end state (ES) or mid-state (MS). Thus, with respect to a given ES or MS, this template asks "How could I cause this state to occur?"

In the context of Risk Analysis, this ES or MS would be hypothesized as a possibility. But it might be that such a state has actually occurred in the real-world system. In this case, the application of the AFD question would be a Failure Analysis process, i.e., an attempt to determine the cause of a failure that has actually occurred. Thus we see that the Failure Analysis template can be used either for risk analysis, with hypothesized ESs and MSs, or for failure analysis, with a failure event that has actually occurred. For this reason we refer to the AFD-1 template also as the Failure Analysis Template.

The Failure Prediction template (Appendix 2) helps us develop the incoming trees to specified ESs and MSs. This template is similar to the Failure Analysis template, except that it includes the process of identifying the ESs and MSs, and IEs.

An example of the application of Failure Prediction to a fender manufacturing process is given in Appendix 3.

8. Failure Prevention/Elimination as the Final Part of the AFD Process

"Preventing causes costs less then overcoming consequences"

One of the main goals of the AFD is to not only reveal or predict the failure but to eliminate it effectively and in a timely manner. For this purpose, a tool for preventing or eliminating failures constitutes the final step of the AFD process (see attachment #4 "Prevent or eliminate the drawback").

The main idea of the "Prevent or eliminate the drawback" is the following:

> *The ideal way to prevent a drawback or failure is to eliminate its causes. There are many reasons, however, why this might not be possible – it might be too expensive, too late, outside your area of responsibility, etc. Whatever the case, make your selection from the following:*

If you wish to prevent the drawback from appearing, select:

Eliminate the causes of the drawback

To prevent the harmful effects of the drawback, select:

Eliminate the drawback

If the above two choices are not possible, try

Eliminate the effects of the drawback:

This section of the software includes lists of innovation recommendations called operators. To utilize an operator, the user should:

1. Read the operator. Try to mentally apply it by drawing analogies to your situation.
2. Review any additional references for that operator.
3. Review the associated examples, trying to understand their relevance to the operator.

9. The I-TRIZ Analytical (Inventive) Methods

We have already described the I-TRIZ analytical methods to some extent, and much more information is available in references [1], [2], and [10]. Here we will not repeat this information but only point out, first, that these analytical methods (which include the Innovation Guide), can be understood as illustrations of the Principle of Solution by Abstraction set forth in Figure 6 of reference [2], and repeated here as Figure 28.

Secondly, we would like to point out that the "Specialization" step in the above-mentioned figure is tantamount to the "secondary problem" in ARIZ. By placing this problem in the lower left corner of the figure, we can again apply the abstraction principle to the secondary problem, using whichever of the I-TRIZ analytical methods seems most suitable. This can be repeated until a final satisfactory solution is reached. Thus we see that ARIZ can be viewed (see Figure 29) as an iterative application of the solution schema of Figure 28.

Similarly, recognizing that solving a secondary problem usually requires the application of resources, we are led to another very powerful view of the ARIZ iterative process, as shown in Figure 30.

10. Summary and Conclusion

The subject of this book has been finding potential failure scenarios in our systems, facilities, operations, plans, etc., before they actually occur. We reviewed the traditional methods used for this purpose, and then introduced a new method, *Anticipatory Failure Determination (AFD)*, which we have shown to be the application of I-TRIZ to the subject of Quantitative Risk Analysis (QRA). QRA is concerned both with finding scenarios and quantifying their likelihoods and consequences. AFD therefore applies to the "qualitative" part of QRA – the part that has to do with finding the risk scenarios. As such, it joins the traditional methods, such as FMEA and HAZOP, currently used for finding scenarios. The questions therefore arose: How is AFD different from the existing methods? What are its "pros" and "cons"? And why should we be interested in it?

To answer these questions, we presented what we call the *Theory of Scenario Structuring*, which is a kind of geometry on the set of all possible failure scenarios. This theory provides a unifying structure against which the various methods can be understood, and compared. Central to this structure are the idea of a scenario tree and its subtypes: the event tree, fault tree, mixed tree, and subsidiary tree, all of which represent different "angles of attack" to a failure problem. An interesting observation is that AFD seems to attack from all directions at once. It is a particularly thorough and comprehensive approach, as well as an insightful one. Moreover, since it is relatively new, it has much potential for growth and for becoming more powerful and useful.

It is the opinion of the authors that AFD has much to offer to the practice of risk assessment, and will have more in the future. In particular, we have suggested that the checklist idea used in AFD can provide a framework within which the entire human experience in building and operating various systems and facilities – including the experience with failures of equipment and human error – can be organized, codified, the principles abstracted, etc. This body of knowledge, which would be continually growing, could be placed on the web and made available to engineers and others worldwide.

Software based on the AFD method is available for the failure analysis and failure prediction processes. These products are produced and distributed by Ideation International Inc. and are designed to be useful for beginners as well seasoned risk analysts. Both applications include automatic formulation of the inverted problem as well as the automatic selection of operators. (Appendix 4 lists some of the features of the latest versions of the AFD software.)

APPENDIX 1
Template for Failure Analysis (AFD-1)

STEP 1. FORMULATE THE ORIGINAL PROBLEM

Describe the original situation associated with the undesired phenomenon:

There is a system called [name of system] **for** [describe purpose of system]. **An undesired effect occurs under the conditions** [describe]. **It is necessary to find the cause of this phenomenon.**

STEP 2. IDENTIFY THE SUCCESS SCENARIO

Operations or Phases	Results

STEP 3. LOCALIZE THE FAILURE

STEP 4. FORMULATE AND AMPLIFY THE INVERTED PROBLEM

Step 1. **It is necessary to produce** [describe inverted problem] **under the given conditions** [describe].

Step 2. **It is necessary to produce** [describe inverted problem] **under the given conditions** [describe amplified conditions].

STEP 5. SEARCH FOR SOLUTIONS

The same phenomenon is intentionally created in the following areas:

The resources (available or derived) are:

The way(s) to produce the desired phenomenon as found in the Innovation Guide are:

ARIZ for Failure Analysis

Step 1. The general way to produce the desired phenomenon is:

The secondary problem is:

Step 2. The ideal conditions for realizing this harmful phenomenon are:

Step 3. The known way to provide the ideal conditions is:

The way to change the system, recommended by the Innovation Guide is:

Step 4.

A - Limitations to providing the ideal conditions are:

B - Contradiction: There is a way to produce the harmful effect

but it cannot be realized for the following reason:

C - According to the Separation Principles, this contradiction may be resolved in the following way:

STEP 6. FORMULATE HYPOTHESES AND TESTS FOR VERIFYING THEM

The hypotheses are:

Tests required to verify the hypotheses:

STEP 7. CORRECT THE FAILURE

The way to prevent / eliminate this kind of failure in the future is:

APPENDIX 2
Template for Failure Prediction (AFD-2)

STEP 1. FORMULATE THE ORIGINAL PROBLEM

Describe the original situation associated with the undesired phenomenon:

> **There is a system called** [name of system] **for** [describe purpose of system]. **We wish to find all possible undesired effects or failures that can occur within, or as result of, this system, and to identify the ways in which these undesired phenomena can occur.**

STEP 2. IDENTIFY THE SUCCESS SCENARIO

Operations or Phases	Results

STEP 3. FORMULATE THE INVERTED PROBLEM

> **There is a system called** [name of system] **for** [describe]. **It is necessary to produce all possible undesired effects or failures that can occur within, or as a result of, this system.**

STEP 4. APPARENT WAYS TO DETERIORATE THE SYSTEM FUNCTION

Obvious possible Initiating Events are:

Obvious Harmful End States are:

Obvious Possible Risk Scenarios are:

STEP 5. IDENTIFY AVAILABLE RESOURCES

Substance resources:

Field Resources:

Space resources:

Time resources:

Functional resources:

Systemic resources:

Change resources:

Differential resources:

Inherent resources:

Organizational resources:

Small failures disturbances:

Hazardous elements:

Control devices:

Protection systems:

STEP 6. UTILIZE THE KNOWLEDGE BASE

Typical weak and dangerous zones in a system:

Typical functional failures:

Typical harmful impacts on systems (humans included):

Typical life cycle stages of technological systems:

Typical dangerous periods in system functioning and evolution:

Typical sources of high danger:

Typical disturbances in flows of substance, energy and information:

Resources:

STEP 7. INVENT NEW SOLUTIONS

The way(s) to produce the harmful effects according to the Innovation Guide are:

ARIZ for Failure Prediction

Step 1. The general way to produce the desired effect is:

The resulting secondary problem is:

Step 2. The ideal conditions for realizing this harmful effect are:

Step 3. The known way to provide the ideal conditions is:

Step. 4. The way to change the system, as recommended by the Innovation Guide, is:

   A - Limitations to providing the ideal conditions are:

   B - Contradiction – There is a way to produce the harmful effect but it cannot be realized for the following reason:

   C - According to the Separation Principles, this contradiction may be resolved in the following way:

STEP 8. INTENSIFY AND MASK HARMFUL EFFECTS

Typical ways to intensify harmful effects:

Typical ways to mask harmful effects:

STEP 9. ANALYZE THE REVEALED HARMFUL EFFECTS

STEP 10. PREVENT/ELIMINATE THE HARMFUL EFFECTS

Typical ways to prevent harmful effects:

Results of working with I-TRIZ operators:

APPENDIX 3
Case Study for Failure Prediction

Fender Manufacturing

I-TRIZ specialists were asked to improve a bike manufacturing process. Below is an account of a small part of that project, which had to do with the search for potential problems in the rear fender manufacturing process.

Figure 32. Bicycle

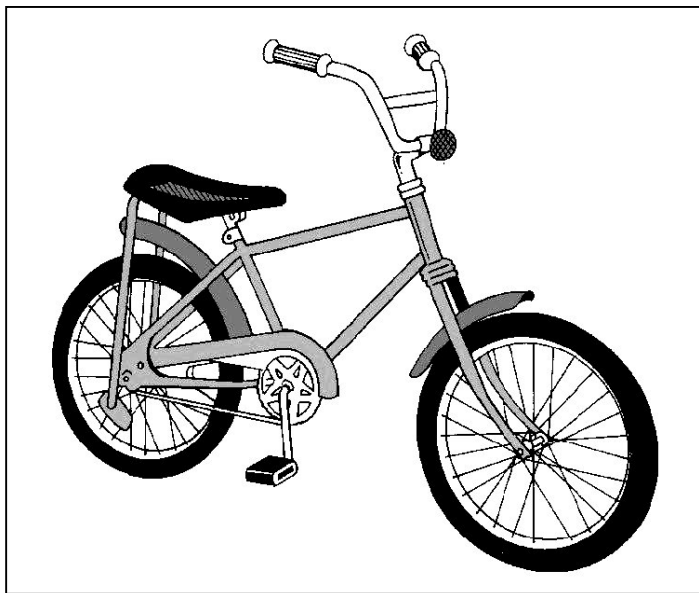## STEP 1. FORMULATE THE ORIGINAL PROBLEM

There is a system called *Rear Fender Manufacturing Process* **for** *manufacturing bicycle fenders.* **We wish to identify all possible failures, harmful events, or undesirable phenomena that can occur during this process.**

STEP 2. IDENTIFY THE SUCCESS SCENARIO

The success scenario of the fender manufacturing process includes the following five phases:

OPERATION	RESULTS
Fender stamping	Stamped part of desired shape
Washing the fender with hot water solution of hydrochloric acid	Removal of oil required for stamping
Polishing the outer surface of the fender	Outer surface prepared for coating
Washing the fender after polishing	Removal of particles of the composition used for polishing
Electrochemical coating of the outer surface with layers of nickel and chromium	Part ready for assembly

STEP 3. FORMULATE THE INVERTED PROBLEM

We desire to identify all possible ways in which we could bring about all the possible undesirable phenomena that can occur during this process.

STEP 4. APPARENT OR OBVIOUS WAYS TO DETERIORATE THE FUNCTIONING OF THE SYSTEM

Obvious Possible Initiating Events. In this example we do not assume any particular knowledge of similar manufacturing systems. We can, however, ask the inverted question "How can we create deterioration of the system?" and then, based on the above phases of the success scenario, define the following Initiating Events:

IE1: Improper stamping process

IE2: Errors during washing after stamping

IE3: Bad polishing

IE4: Bad washing after polishing

IE5: Poor coating

(These are actually categories of initiating events)

Obvious Harmful End States. Similarly, we can imagine what to the plant managers must be the ultimate harmful end states (**HESs**):

HES1: Increased cost of production, per fender

HES2: Reduced sales

HES3: Unhappy customers

HES4: Damage to worker health

HES5: Damage to environment

HES6: Damage to plant and equipment

Obvious Possible Risk Scenarios.

    S1. IE1 → increased stamping waste → HES1

    S2. IE2 → IE3 → IE5 → HES2

    S3. IE3 → IE5 → HES2

    S4. IE4 → corrosion after purchase → HES3 → HES2

    S5. IE5 → HES2

Although these scenarios are the obvious ones, we can already see emerging in them certain scenario structuring ideas that are important.

First, for example, note that we have introduced mid-states (**MSs**), such as "increased stamping waste," between the initiating events and the end states (**ESs**). Note also that **IEs** and **ESs** can also serve as **MSs** in other scenarios.

Second, we can see that even in this relatively simple manufacturing process there will be a profusion of possible scenarios. It will therefore become important to use scenario trees, along with a numbering system, to impose some orderliness and control on this profusion.

Third, the **IEs** and **HESs**, as we have defined them so far, represent large categories of events. Our task will be to break these large categories into subcategories and thus to identify more specific scenarios which we can then take actions to eliminate. To do this we will stimulate our creative thinking by using the **AFD** checklists, as follows.

STEP 5. IDENTIFY AVAILABLE RESOURCES

We first look through "Resources" to become aware of the resources present that can help to create harmful effects:

TYPE OF RESOURCE	DESCRIPTION
Substance Resources	
Waste	Stamping waste
	Evaporation of chemicals (hydrochloric acid) used for fender washing.
Raw materials/products	Stamping steel
	Polishing paste
	Chemicals used for nickel and chromium plating.
Field Resources	
Fields (energy) in the system	Mechanical energy of the punch.
	Electrical current used for electrolytic coating.
Fields (energy) from the environment	Air flow due to ventilation.

Space Resources	Various contaminants that can remain on the fender's inner surface.
	Fender edges and corners that are usually more difficult to coat with the same quality as the other parts of surface.
Time Resources	
Preliminary action	Micro-cracks, residual stresses in the fender, etc., developed during manufacturing.
	Corrosion nuclei in the fender can develop during fender manufacturing.
Using available post-process time	Chemically active substances deposited on the fender during the manufacturing process can contribute to the gradual destruction of the fender.
Functional resources	Nickel/chromium plating of the fender's inner surface leads to increased consumption of these expensive materials.
Systemic Resources	The presence of hot water-hydrochloric acid vapors in the air, ventilation air flow, storing of polished fenders before coating.
Organizational Resources	Disturbances in the distribution of current lines on the fender's outer surface lead to non-uniform coating thickness and coating of some zones on the fender inner surface.
Hazardous Elements	Chemically active substances used in the manufacturing process.

We next use the AFD checklists to provide more detail on the above scenarios and to identify additional ones. We begin by drawing outgoing scenario trees (see Figures 1 to 5) for each IE, and numbering the additional IEs and MSs correspondingly.

STEP 6. UTILIZE THE KNOWLEDGE BASE

We begin by comparing our fender manufacturing system against the checklist **Typical Weak and Dangerous Zones in a System.**

ZONE TYPE	POSSIBLE DANGER SOURCES
Flow concentration zones	Washing and drying zones – flow of air and water
	Stamping zone – flow of lubricant, mechanical forces, impacts
	Coating zone – flow of electrical energy

Zones subjected to the action of high-intensity fields	Stamping zone – mechanical forces, impacts, vibrations
	Coating zone – high-amplitude electric current, etching chemicals
Conflict zones	Parts washing zone: an acid is added to washing water to improve washing, yet this acid can cause corrosion
"Bad history" zones	Harmful effects: Rejects (defective parts) are usually related to the polishing and coating zones
Zones of junctions between different systems	Storage zone (where parts are stored after polishing)
Multi-function zones	In the coating zone are many electroplating tanks. This zone is used to perform functions such as parts washing, electrolytic etching, coating with several layers of nickel and then chromium, etc
Tool-article contact zones	Stamping zone – mechanical forces, impacts, vibrations

This checklist calls our attention to a zone we had not identified before – the storage zone – and suggests we define another **IE** as **IE6**: Something goes wrong in the storage zone between the polishing and washing operations.

Also, the reference to "flow of lubricant" in the stamping zone suggests the initiating event "incorrect lubrication," which we shall consider as a subset of **IE1**, and therefore label **IE1.3** in the scenario tree emerging from **IE1**.

CHECKLIST: Typical Functional Failures

Technological Systems (i.e., failure of function at the system level):

"Unexpected decrease of performance" suggests "decreased production rate," which we regard as a subset of **HES1**, and therefore label **HES1.1**.

"Harmful impact on people" suggests **HES4**.

"Harmful impact on environment" suggests **HES5**.

Devices (failure at the device level):

"Change of dimensions" suggests "incorrect dimensions of fender." We regard this as a mid-state and label it **MS1.2**.

"Contact conditions and relative location of elements" suggests "misplacement of blanks," which we regard as another sub-case of **IE1**, and label as **IE1.1**.

Components:

"Change of shape" suggests "deformed fender." Call this MS1.3.

"Change of surface conditions" suggests IE3 and IE5.

"Corrosion" suggests "corrosion after purchase." We shall call this HES7.

Materials:

"Cracks, fractures" suggests micro-cracks in the fender. Call this MS1.4.

"Deformations" suggests MS1.3.

"Change of hardness, elasticity, impact strength," suggest "wrong steel." Call this IE1.2.

"Aging, corrosion" suggests HES7.

"Evaporation of volatile" suggests excess evaporation of washing fluids (call this IE2.3, and IE4.3) and of electrolyte (call this IE5.3).

Objects of nature:

"Environmental pollution" suggests IEs 2.3, 4.3, 5.3 and HES5.

"Disappearance of useful substances" again suggests IEs 2.3, 4.3, and 5.3, now leading to HES1.

CHECKLIST: Typical Harmful Impacts

Mechanical:

"Impacts, jolts, mechanical stresses" suggests **IE1.4**.

Electrical:

"Impacts of electrical field, discharges, current" suggests disturbances of electric current (call this IE5.1) causing poor coating (call this MS5.1).

CHECKLIST: Typical Disturbances in Flows of Substance, Energy and Information

This checklist prompts us to identify additional scenarios, as follows:

S6: "Traffic schedule disturbance" (call this **IE6**) leads to accumulation of parts after polishing and long waits between polishing and coating (**MS6.1**). This results in corrosion of the polished surface and therefore corrosion of the coated surface after purchase.

"Change in flow magnitude" suggests fluctuations of the electrical current magnitude which we have already included as **IE5.1**.

"Flow directed into the wrong place" and "disturbance of spatial flow structure" suggests that, in addition to fluctuations of current magnitude, there is the possibility of disturbance in the spatial flow pattern of electrical energy during nickel/chromium coating. Considering this possibility leads to identification of another branch (**IE5.2**) in scenario tree **S5** as follows:

The inner surface of the fender is distanced from the electrodes, yet because of the spreading of electric current lines in conductive media, some amount of nickel is deposited on this surface (**MS5.2**). This nickel does not form a solid film, but instead forms small spots. Nickel and steel in the presence of water develop a galvanic action in which steel becomes a sacrificial material. This corrosion phenomenon develops after the

bicycle is sold and leads to dissatisfied customers and reduced sales. There is 100% probability of this scenario developing. It occurs in each fender to some extent.

CHECKLIST: Typical Resources

This checklist leads us to some of the previous scenarios and also identifies some new scenarios, as follows:

TYPE OF RESOURCE	SUGGESTED SCENARIOS
Substance Resources	
Waste	Inefficient location and spacing of blanks is a sub-case (**IE1.1**) of **IE1** that leads to increased stamping waste and cost.
	IE4.3, evaporation of chemicals (hydrochloric acid) used for fender washing before nickel and chromium plating, can lead to health damage, increased cost from lost chemicals, and to intense shop-floor equipment corrosion (**HES6**).
Raw materials/products	Stamping steel. If the materials requirements for the stamping operation are not met (**IE1.2**), intense die and punch wear can result (**MS1.5**).
	Some of the chemically active ingredients of the polishing paste can cause development of corrosion nuclei on the fender's inner surface (the branch of tree **S4** passing through **IE4.1**).
	Chemicals used for nickel and chromium plating can cause corrosion of unprotected surfaces (**IE5.4** branch). These substances are also skin irritants.
Inexpensive substances	Water, actually dilute HCl, used for fender washing after stamping, can cause corrosion of the unprotected surfaces. See **IE2.2**.
Field Resources	
Fields (energy) in the system	Mechanical energy of the punch can lead to development of harmful stresses in the parts which may result in parts deformation (**MS1.3**).
	Electrical current used for electrolytic coating. Due to spreading of the current, the nickel/ chromium plating takes place not only on the fender's outer surface but on the inner surface as well. This leads to galvanic corrosion (**MS5.3**) and increased consumption of materials (**MS5.4**).

Fields (energy) from the environment	Air flow due to ventilation contributes to the spreading of harmful electrolytic vapors throughout the shop (**IE5.3**).
Space Resources	Various contaminants can remain on the fender's inner surface. Since access to this zone is difficult, these contaminants can cause rapid fender corrosion (**IEs 2.2, 4.1,5.4**). Fender edges and corners are usually more difficult to coat with the same quality as other parts of the surface (**IE5.5**).
Time Resources	
Preliminary action	Micro-cracks, residual stresses in the fender, etc., developed during manufacturing, can cause the fender to fail during operation of the bicycle (**IS1.5**). Corrosion nuclei in the fender can develop during manufacturing (**ISs 2.2, 4.3, 4.4**).
Using available post-process time	Chemically active substances deposited on the fender during the manufacturing process can contribute to gradual destruction of the fender (**IEs 2.2, 4.3, 4.4, 5.4**).
Systemic resources	Hot water-hydrochloric acid vapors in the air (**IE2.3, 4.3**) + ventilation air flow + storing of the polished fenders before coating (due to mismatched rhythms of stamping, polishing and coating) (**IE6**) cause corrosion to develop on the polished fender's surface.
Organizational Resources	Disturbances in the lines of current flow (**IE5.2**) lead to non-uniform coating thickness and coating of some zones on the inner surface.
Hazardous Elements	Chemically active substances used in the manufacturing process lead to corrosion after purchase.

STEP 7. INVENT NEW SOLUTIONS

ARIZ for Failure Prediction

Describe the secondary problem or obstacles. We need to cause corrosion of the fender. The water used for washing the fender contains acid that can cause corrosion. This acid is too weak, however.

Describe the ideal conditions for realizing this harmful effect. The ideal conditions are: Weak acid causes noticeable steel corrosion in the most hazardous locations on the fender, and without any changes to the system.

Is there a known way to provide these ideal conditions? To provide for steel corrosion we need to make the acid stronger; that is, remove water from the solution and thus increase the strength of the acid. The Innovation Guide recommends evaporation as one way to remove a substance.

A more detailed examination of the manufacturing process revealed the following: When the fender is ready to be washed, it is suspended on a conveyer with its outer surface upright, and is sprinkled with a dilute water-based acid solution while in a special booth. The fender hangs on the conveyer until it is dry. As it dries, drops of solution remain on the fender. The evaporation rate of water is much higher than that of the acid, so the drying process is accompanied by an increase in acid concentration, eventually resulting in a concentration level sufficient for initiating corrosion.

Thus we have spelled out more details of the scenarios leading to the development of corrosion nuclei that, in turn, lead to rapid corrosion after the bike has been sold. The corrosion is more intense on the fender's inner surface and on its edges, due to the high relative concentration of the solution drops.

STEP 8. INTENSIFY AND MASK HARMFUL EFFECTS

As pointed out in the *Resources* checklist under "systemic resources," combinations of harmful effects can be much more harmful than the effects acting separately. In the current case, for example, the corrosion nuclei that develop on the fender's inner surface act together with the nickel drops to intensify the corrosion.

Another intensifying mechanism is the development of a "chain" of harmful effects. The corrosion nuclei and nickel drops cause corrosion on the inner surface and edges of the fender. This corrosion then spreads underneath the coating, leading to the development of crevice corrosion. The crevice corrosion causes the surface of the fender to rust underneath the coating, and the coating flakes as a result. This, in turn, causes more rapid corrosion of other areas of the fender.

STEP 9. ANALYZE THE REVEALED HARMFUL EFFECTS

The various scenarios can be presented in the form of outgoing scenario trees or in the form of incoming trees. There are many ways to make these diagrams and to categorize and label scenarios. You may wish to rearrange or improve on the ones shown here to suit your own way of looking at the situation.

STEP 10. PREVENT / ELIMINATE THE IDENTIFIED FAILURE SCENARIOS

The most interesting harmful scenario identified during this study was that which involved the galvanic corrosion from nickel spots deposited on the inner surface of the fender. (See **IE5 → IE5.2 → MS5.2 → MS5.3**.) To develop concepts for eliminating this scenario, we go to the *Prevention/Elimination* section of the software and use the I- TRIZ operators. Four groups of operators are listed. Simply looking at the names of the operators brings the following suggestions to mind:

> 1) Eliminate the causes, i.e., the conditions that cause the undesired action.

> 2) Introduce a process that eliminates or reverses the effect of the undesired action.

Eliminate the conditions that cause the undesired action. If we take the undesired action to be the depositing of the nickel spots, then the cause is the spreading of the electric current. Eliminating this cause would require major alterations to the entire electroplating process and to the design of the electrolytic tanks, and would therefore be too costly.

Provide a counteraction by means of another action. If the undesired action is the depositing of the Ni, then the effect of this action is the deposits themselves. The second suggestion, then, is to introduce another action that removes the deposited nickel after the coating process is finished.

At the end of the coating process, to make the part more shiny, a very thin layer of the coating is removed. This is accomplished by switching on a so-called reverse current. It was therefore proposed that special reverse current electrodes be placed in the tank, in the vicinity of the fender's inner surface, which would effect the removal of the nickel from the inner surface and thus prevent the corrosion.

Isolation. The first suggestion above eliminates the cause of the action; the second eliminates its effect. A third possibility would be to coat the fender's inner surface with an electro-insulative layer before electroplating. This would prevent the nickel deposition and protect the fender from other types of corrosion. Again, however, this would result in an increase in cost.

Intensifying the undesired action. Since the above three suggestions have not led us to a satisfactory solution, we look further by selecting the group *Eliminating the Failure*, then the subgroup *Impact on an Undesired Action*, and finally on the operator *Enforcement of an Action*, which reads as follows:

> **Consider increasing the intensity of a harmful effect to the point where the effect is eliminated.**

This sounds like an application of the proverb "If you can't beat 'em, join 'em," and does prove to be a fruitful idea. The ultimate harmful effect is corrosion that results from the deposition of nickel spots. If there were more nickel on this surface, the result would be the development of a solid coating layer and thus the corrosion would not develop. This could be achieved through redesign of the electrolytic tanks, electrodes and coating scheme. An increase in nickel consumption would result, but might be worthwhile since warranty expenses would be reduced and customers' expectations would be met.

APPENDIX 4
Anticipatory Failure Determination® Software Features

There are two software products for Anticipatory Failure Determination: Ideation Failure Analysis and Ideation Failure Prediction. Both products include the following features:

1. Templates and Suggestions for Failure Analysis and Failure Prediction

Hypertext templates to guide you through the failure analysis or failure prediction process, along with explanations and suggestions for each step.

2. Problem Formulator®, which provides:

- A means to create a graphic model of the system, its environment, and related failures (either existing or hypothesized).

- Automatic generation of problem statements to support the development of failure hypotheses. These include:

  - For Failure Analysis – the *Inverted Problem Statement* for any failure or drawback whose cause you aim to reveal.

  - For Failure Prediction – a set of Directions for each function (activity, action, process, operation, condition, or effect) included in the system model.

  - A set of *Directions for Failure Prevention/Elimination* for each verified failure or failure scenario.

- Embedded links from each Direction to the applicable section of the AFD knowledge base.

3. AFD Knowledge Base

The AFD Knowledge Base includes:

- System of Operators – The I-TRIZ principles, methods and standard solutions in the form of recommendations for changing a system. In AFD failure analysis and prediction, operators are used to help generate hypotheses and ideas for corrective action.

- AFD checklists
  - Typical functional failures
  - Typical harmful impacts
  - Typical stages in the lifecycle of a technical system
  - Typical weak and dangerous zones
  - Typical dangerous periods in a system's functioning
  - Typical sources of high danger
  - Typical disturbances of flows
  - Typical resources capable of producing harmful impacts
  - Patterns of typical failure scenarios (including human errors)

- Methods of intensifying a failure
- Ways to mask or hide a failure

- Innovation Guide – a hypertext encyclopedia of technological effects useful for failure analysis and failure prediction.

4. AFD Report

The AFD Report offers the ability to document your creative work with the software. Reports can be converted to rtf files for use with other applications.

5. Illustrations

Each operator is accompanied by one or more illustrations describing how the operator was applied to a specific technological situation.

About the Authors

Stan Kaplan holds a B.S. in civil engineering and a Ph.D. in mechanical engineering and applied mathematics. He was one of the early practitioners of the discipline known as Quantitative Risk Assessment (QRA), and is a major contributor to its theory, language, philosophy and methodology.

Dr. Kaplan has applied QRA to a wide range of industries, including the space, defense, and nuclear industries, manufacturing processes, and hazardous materials storage and transportation. He worked with the U.S. Department of Agriculture to apply QRA to regulating the importation of animals and fruits, and contributed to the U.S. Navy's nuclear propulsion program with analyses of the xenon spatial stability problem, space-time kinetics, and the development of the Kaplan synthesis methods in reactor physics.

Other contributions include the development of the discrete probability distribution (DPD) method for probabilistic calculations, the two-stage Bayesian technique for data analysis, and the *set of triplets*, *probability of frequency*, and *cause table* concepts in risk analysis. He is the originator of the matrix theory of event trees, the DPD approach to seismic risk analysis, and the "expert information" (or evidence-based) approach to eliciting/combining knowledge from experts.

He is the founder and CTO of Bayesian Systems Inc., a Washington, D.C.-based company that develops diagnostic and decision software. In 1996, Dr. Kaplan received the Distinguished Achievement Award from the Society for Risk Analysis. He was elected to the National Academy of Engineering in 1999.

Dr. Kaplan is one of the first American scientists to become interested in, and contribute to, the Russian Theory of Inventive Problem Solving (TRIZ). In addition to its evident practical value, he was attracted to the notion of a structured approach to creative thinking that could be applied to any human endeavor – engineering inventions, business strategies, political and social organization, military operations, pure science, or even artistic expression.

Svetlana Visnepolschi received an M.S. in electronics from the Leningrad Institute of Precision Mechanics and Optics in 1976. She became a student of Genrich Altshuller, the originator of TRIZ, in 1983. Her early contributions to TRIZ include the creation (with Boris Zlotin) of the working algorithm for *TRIZ resources*. She later pioneered various projects in the application of TRIZ prediction methods to the development of both technological and non-technological systems; included with the latter are the Moscow Stock and Commodity Exchange and the Moldovian presidential election campaign. Ms. Visnepolschi has been teaching TRIZ to engineers for more than 15 years, and is co-author, along with Boris Zlotin and Alla Zusman, of a number of TRIZ publications. Since 1985, she has been involved in the research, development and application of the TRIZ-based Anticipatory Failure Determination (AFD) methodology. She is the designer of Ideation International's AFD software.

Boris Zlotin was already an experienced inventor, with a B.S. and M.S. in electrical engineering from St. Petersburg Polytechnic University, when he was introduced to TRIZ in 1974. He decided to devote himself to the methodology and was soon applying TRIZ to

various industries as well as teaching TRIZ to university students and engineers. He began working with TRIZ originator Genrich Altshuller in 1981, and in the ensuing years they jointly authored several books on TRIZ and conducted seminars throughout the Soviet Union. Mr. Zlotin's numerous contributions to the methodology during this time included developing the *lines of evolution* and devising a method for using TRIZ to solve scientific research problems. In 1982, Mr. Zlotin co-founded the Kishinev TRIZ School, which led the research and development of the methodology after Altshuller became ill. Since 1992, he has been Chief Scientist and Vice President of Ideation International, where he provides and directs TRIZ consulting services throughout a broad range of industries. With the Ideation Research Group, Mr. Zlotin continues advancing the methodology and inventing new TRIZ applications in both technical and non-technical domains. To date, he has facilitated the solution of more than 4,000 technical and business problems, authored twelve books and numerous articles, and taught more than 5,000 students.

Alla Zusman holds a B.S. and M.S. in radio-physics from St. Petersburg Polytechnic University, and was an experienced research engineer and patent agent when she began working with TRIZ in 1981. She has since become a leader in both the teaching and application of the methodology, having founded (along with Boris Zlotin) the Kishinev TRIZ School in the Soviet Union. Ms. Zusman's advancements to TRIZ include the development of the theoretical base for TRIZ software, the design and teaching of the U.S. adaptation of the methodology, and the development of new applications for solving scientific and business problems. She has more than 5,000 hours of teaching experience and has taught more than 4,000 students. Ms. Zusman has co-authored eight books on TRIZ (including one with TRIZ founder Genrich Altshuller) and written many articles in both Russian and English. She is currently the Director of Product Development for Ideation International.