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INTEGRATION OF FAILURE MODE IDENTIFICATION WITH DESIGN FOR MECHANICAL COMPONENTS

by

J. L. Handrock and D. L. Marriott

Materials and Design Division
Department of Mechanical and Industrial Engineering

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ABSTRACT

Component failure is always expensive, even when failure is not an issue from a safety point of view. The cost of detecting and rejecting defective parts increases exponentially as the product development process advances. The ideal place to correct errors is right at the beginning of the process, before any commitment has been made to materials or manufacturing processing methods.

This paper considers the problem of identifying all sources of possible component failure, including such off-design situations as material substitution and gross human errors. Because of the large number of opportunities for such errors to exist in a typical production process, and recognizing the fact that relatively few of these errors are likely to be a real problem in a specific case, the problem which must be solved is one of searching for a sparsely distributed set of significant events in a large population of irrelevant events. A strategy is presented herein, which allows efficient use of existing information available to the designer to be used to converge rapidly onto the possible failure events, as a preliminary study to detailed analysis of each individual failure mechanism.

The strategy developed for failure mode identification is illustrated by application to an example of the manufacture of a vehicle suspension spring. The events leading to accelerated failure due to error-induced fatigue mechanisms are identified, and the results of the study are used to illustrate how an analysis of this type might be used to plan Quality Assurance activities on a Fitness-for-Purpose basis.

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1. INTRODUCTION

Component failure is always expensive, even when failure in service is not an issue from a safety point of view. The cost of detecting and rejecting defective parts is known to increase exponentially through the product development cycle. Therefore, the ideal place to correct any errors is right at the beginning of the cycle, before any commitment has been made to materials or processing.

Anticipating and preventing potential errors is basic to the engineering design process. Nevertheless, despite all the precautions taken failures still occur. The object of this paper is to examine the causes of these failures, present a model which explains why failures in service persist despite the best efforts of all concerned, and offer one strategy for the systematic reduction of their occurrence rate. In doing so it is believed that a basis is offered for the eventual unification of the activities of design, reliability, risk assessment, and quality assurance.

2. A REVIEW OF MECHANICAL RELIABILITY CONCEPTS

Conventional reliability theory presumes that virtually all components will fail, in one way or another, if operated long enough. Considering a large population of nominally similar components the instantaneous failure rate, or hazard rate, is characterized by a curve as shown in Figure 1. This is commonly known as the "Bathtub Curve". Typically it has three zones which are identified with fundamentally three different types of failures:

I. Burn-in Phase

A decreasing failure rate represents the gradual elimination of initially defective components from the population.

II. Constant Failure Rate Phase

Failure is commonly attributed to random external events which exceed the normal capacity of the component.

III. Wearout Phase

Deterioration mechanisms which limit the components life begin to appear, causing the failure rate to increase.

Service experience shows the majority of mechanical failures to occur by wearout mechanisms of various forms, notably fatigue and corrosion [1,2]. The immediate conclusion, and one which is quoted frequently in the literature on reliability [3], is that mechanical components are expected to show increasing hazard rate curves. The mechanism of mechanical failure can be explained by the well-known load-strength interaction diagram (Fig. 2a) which predicts a finite failure probability because the tails of the load and strength distributions will, in general, overlap. There is extensive literature based on models of this kind, virtually all of which assume, implicitly at least, that the primary cause of deviation from some nominal state is the stackup of random variations, as might reasonably be expected even in a controlled production process (e.g., Haugen [4]). With this model in mind it is a natural consequence to assume that the road to improved reliability is through the following actions.

1. Improved understanding of wearout mechanisms.
2. Improved techniques for predicting component behavior.
3. Development of probabilistic methods of component behavior to deal with random factors.

The object of the next section is to compare these assumptions with evidence from service failures.

3. COMPARISON OF RELIABILITY CONCEPTS WITH EXPERIENCE

A detailed evaluation of service experience suggests that the common wisdom regarding the causes of mechanical failure does not correspond well with observations. Generally speaking, failure is always accompanied by events, or series of events, which are simply not considered in the initial component assessment. Very seldom does one find a failure which can be clearly attributed entirely to random variations within normal statistical control. In effect the failures considered at the design stage never happen, and observed failures are usually overlooked by the design process. This suggests that, contrary to the conclusions drawn earlier, designers' resources in terms of knowledge of failure mechanisms and methods of component analysis are largely adequate to the task, because failures are avoided quite successfully as long as the basic mechanisms have been recognized. The problem lies in recognizing all the mechanisms early enough in the process to do something about them. This is not an easy task, and it is made more difficult by the fact that it is not generally recognized that two classes of failure mechanisms exist.

1. EXPECTED DESIGN CRITERIA - These are mechanisms which are a normal consequence of the expected operating conditions of the component, such as fatigue in a cyclic loading situation or creep at elevated temperatures. Expected design loads are an integral part of the process of quantitative analysis leading to the choice of materials and scantling sizes.

2. ERROR INDUCED MECHANISMS - These are mechanisms which should not occur in the normal course of events but are brought about by an error somewhere in the product development process. Examples of this type are stress corrosion due to accidental use of stainless steel

welding rod in a ferritic weld, or a failure mechanism which was not anticipated during design.

Usually, the second class, which is either ignored or evaluated in a less than systematic manner, causes most of the problems in service. Given that these two classes of failure exist some inconsistencies between classical reliability concepts and observations of mechanical component performance can be explained. For instance, it is often quoted that mechanical failures are wearout mechanisms [3,5], and for this reason the hazard rate is expected to increase with time. In the case of pressure vessel statistics analyzed by Bush [6] however, it is apparent that the hazard rate has a definite decreasing trend, despite the fact that the actual mechanisms were indeed forms of wearout such as fatigue, corrosion, and creep (see Fig. 3). The reason for this inconsistency is that most of the observed failures were of the second class, i.e., they were error induced. Although the final failure event was by a wearout mechanism it was invariably a form of accelerated wearout induced by some initial defect and not therefore the same type of mechanism considered in the normal course of design. It seems that, in addition to the three commonly recognized categories of failure, illustrated by the "Bathtub Curve" in Fig. 1, a fourth should be recognized with the combined characteristics of both "Burn-in" and "Wearout". Unfortunately this category is not easily identified by examining hazard rate plots, and as a consequence, failures of this type have, in the past, been confused with the other three categories. This distinction may not be very important in interpreting failure rate data simply for the purpose of reliability assessment, but it can seriously inhibit efforts to build in reliability at the design stage.

The relative importance of this fourth mixed class of failure can be seen by studying any collection of failure reports, of which there are several recent publications in the open literature. As one example we will examine the fatigue failures recorded in the ASM Metals Handbook [1]. There are 125 such cases. Table 1 summarizes the causes. Only six conform remotely with the conventional load-strength interaction model commonly used to explain mechanical reliability. The majority are clearly error induced failures which would not be predicted by considering only controlled statistical variations (Fig. 2a). The actual strength distribution is probably more accurately represented by Fig. 2b with a complex multi-modal tail which would be very difficult to model accurately. It is recognized that a collection of case studies, as contained in this reference, does not form a controlled statistical sample. However, it must be assumed that the examples have been chosen to represent a typical cross section of problems, perceived by industry to be important.

It may be concluded that, if we wish to design reliability into products, instead of only improving it by evolutionary methods, we must consider expanding the design process to include this second class of error induced failure mechanism.

4. RELIABILITY IMPROVEMENT BY DESIGN

The obvious means of improving reliability is to systematically eliminate the sources of failure. In the case of expected design criteria this can be achieved by more detailed physical modeling and higher quality material data. However, these devices alone show diminishing returns as the relative proportion of failures caused by expected mechanisms decreases. The dominant form now becomes failure by error induced mechanisms, which poses a different type of problem. Before failure mechanisms can be evaluated they must be identified, and this cannot be done by analyzing the mechanisms already identified in greater detail. We find for instance that,

1. The sources of error can be anywhere in the product development process, from design through operation, sometimes in complex combinations.
2. The mechanisms induced are invariably of a type which would not be predicted by more detailed analysis as normally used to deal with expected design criteria.
3. Improvement in material data is relatively unhelpful unless it includes information on the incidence of, and form taken by, outliers and substitutions.

Expected design criteria are, almost by definition, relatively easily identified. The emphasis in dealing with these failure types is understandably placed on quantitative aspects of physical modeling. On the other hand, the biggest problem with error induced mechanisms is identifying which failures are likely in any specific situation, and what errors are necessary to cause them. This is a complex search problem involving knowledge from many diverse disciplines which, at first sight, appears to be quite insoluble.

Fortunately further observations from case studies indicate a possible solution. The following are common characteristics of actual failure in service.

1. New or unpredictable phenomena are seldom involved. The events leading to failure, once identified, are usually understandable and preventable.
2. In addition to the mechanisms themselves, the actual events leading to failure are repeated, often many times.
3. Material failure mechanisms, by virtue of the physical transformations necessary to cause damage or deterioration, follow distinct logical sequences of events.
4. If anticipated early enough, most error induced failure mechanisms can be controlled.

We conclude that a major gain in reliability can be achieved if only past experience can be harnessed in some way to prevent repeats of previous failure events. This is not a new idea. The value of experience as an intuitive design tool has long been recognized. The problem is how to use it in a systematic and efficient manner. Recently interest has begun to grow in the concept of using past failure experience as a design tool, but as yet the work done in this area is still in its early stages of development. There has been a significant increase recently of publications containing collections of case studies with the stated aim of being used as design aids. However, they do not address the most difficult problem facing a designer, that is how to match up relevant examples from past experience with the current problem. Only Collins and Marriott with their co-workers appear to have attempted this problem. Collins [7] examined about 500 examples of helicopter failures and derived a systematic method for categorizing causes of mechanical failure, which was used to develop a design checklist. This is a useful concept in that it helps to define the full spectrum of potential failure mechanisms, rather than leaving the data in raw form, but it still leaves the task of identifying which mechanisms are relevant in any specific instance to the designer's ingenuity. An alternative approach was taken by Marriott and Beyers [8], since developed further by Marriott and Miller [9], in which the information contained in failure studies was analyzed to reveal logical structural patterns for material failure mechanisms named Material Failure Logic Models (MFLM). These MFLM's form the basis for a systematic search procedure which not only identifies the mechanisms themselves, but also the critical events contributing to failure. The resulting search process can be formalized to a large degree, and is currently the center of research aimed at producing a computer-based design system at the University of Illinois [10,11,12]. Regardless of whether the methods used in the future are computer-based or not it is apparent that improved reliability requires a broader definition of the functions of design. This paper addresses the question of how design practice should be extended to achieve a more comprehensive approach to failure prevention.

5. A BROADER DESIGN STRATEGY OF FAILURE PREVENTION

Failures in practice fall into two classes, of which only expected design criteria are commonly considered. These are relatively easily identified, so that the majority of the effort is expended on quantitative analysis of individual failure mechanisms. To include the second class of error induced mechanisms it is necessary to add another stage to the design process, as shown in Fig. 4. In reliability assessment this procedure is known variously as FMA, FMEA, or FMECA. It is an initial search to determine which of all known failure mechanisms are logically feasible. It is convenient to think of failure analysis as a test against a number of conditions.

1. LOGICAL CONDITIONS - The first requirement is that a failure mechanism must be logically feasible. This means that a favorable set of material, process and environmental parameters must exist before failure is possible. For example, a mechanism may be restricted to a certain material type, temperature range, or stress level, or a complex combination of these parameters.
2. QUANTITATIVE CONDITIONS - Generally speaking governing parameters must achieve certain magnitudes before actual failure occurs.

In the case of expected design loads the logical conditions are automatically satisfied, and only the quantitative conditions need to be considered. Logical conditions only become important when the need arises to include the possibility of error induced mechanisms. This paper offers one possible search strategy and illustrates it by an example involving the design and manufacture of a mass produced spring.

The strategy employed here uses a so-called backward chaining technique. That is, instead of starting with known events and investigating combinations of these to see whether a failure state will arise, the starting point is an exhaustive set of known failure types which are assumed, initially, to be all equally feasible. This set is then compared against the conditions imposed collectively by material choice, service conditions, production processes and any other details of the product development cycle that may be relevant. Each condition acts, in effect, as a filter reducing the feasible set of failure mechanisms to a smaller subset, as shown by the Venn Diagram representation given in Fig. 5. This procedure appears at first sight to be a formidable undertaking, relying as it does on a large prior list of failure mechanisms. In fact this is not the case. It is possible in practice to focus in on the most critical mechanisms very rapidly. The filtering process illustrated in Fig. 6 turns out to be very efficient, as will be shown in an example given later. The only problem arises over the experience required to build the comprehensive set of mechanisms. This can be done in two ways. The first is to invest initial time in developing a generic data bank which can be referred to as needed. The other, used here, is to build a set adaptively to suit the needs of the problem under consideration. This latter approach is practical because the level of detail required to describe failures changes as the assessment progresses. In the early stages, when many possibilities have to be included, only a superficial knowledge is called upon. As the detailed description of processes, material properties, etc. increases the number of mechanisms which satisfy all logical conditions reduces to a manageable number of highly likely candidates, which can be studied in greater depth as needed.

The first step in this filtering process is important, because it enables the total number of mechanisms to be reduced to a relatively small remainder using only superficial or initial information. This is achieved by firstly applying the principle of fitness-for-purpose in a disciplined manner so that only mechanisms which are realistic under the service conditions to be experienced are retained. Secondly, it is not necessary to identify individual failure mechanisms in the initial stages of assessment. To a large extent failure mechanisms can be factorized into classes such as brittle fracture or creep rupture, which are characteristic of reasonably distinct materials or environmental conditions.

6. ILLUSTRATION OF THE STRATEGY BY EXAMPLE

The application of this strategy is best illustrated by an example. We consider here the problem of identifying the modes of failure of a mass produced truck spring. This is a component which was designed specifically to resist fatigue loading as part of its normal operating cycle. In the original design procedure various tests were made to determine the effects on fatigue performance caused by changes in a variety of material properties and manufacturing processes. Consideration was given to cyclic deformation, heat treating effects, presetting (bulldozing), and shot and strain peening. Tests showed that predictions compared favorably with experiments. The design procedures were apparently quite satisfactory in dealing with the expected load case. However, we know that fatigue failure mechanisms can result from abnormal conditions. We propose to show how the design strategy described in previous sections of this paper can be used to provide early identification of these other potential failure mechanisms.

7. FAILURE MECHANISM SEARCH PROCESS

The design strategy examines the data base of failure mechanisms in four stages.

1. Failure Class - The general classes of failure types are specified, including a general description of the material state conditions required to obtain failure, e.g. fatigue, corrosion, etc.
2. Failure Types - Failure types making up each of the failure classes are specified, e.g. decarburization, quench cracking, etc.
3. Failure Elements - The elements forming the sequence of events leading to each failure type are described in basic parameters, e.g. high temperature, plastic deformation, etc.
4. Failure Search - A comparison is made between the elements of each failure and the manufacturing process sequence.

7.1 Evaluation of Failure Classes

The classification list developed by Collins [13] is used here as stage one of the assessment. From his comprehensive list of mechanical failure modes the failure classes presented in Table 2 were identified as being relevant in the present example.

Space does not allow all these classes to be considered. For the purpose of illustration it is sufficient to develop one class in greater detail. This class is fatigue, which is chosen firstly because, from experience, it is the most critical as regards spring behavior and secondly because it emphasizes the difference between fatigue as an expected design condition, and accelerated fatigue, being an error induced mechanism.

For the purpose of identifying significant deviations it is necessary to define the correct state of the final product and its expected duty cycle.

Material - AISI 5160 or 5160H. Both materials are medium carbon steel with low alloying content to ensure deep hardening. The H designation relates to steels containing Boron for use in thick sections.

Microstructure - a) Quenched and tempered to a mean core strength of 1700 MPa (Landgraf [14]). b) Stress peened surface.

Service Conditions - Details are not available, but estimates contained in Appendix A indicates that if cracks in the 0.025 to 0.25 mm range are present fatigue failure by crack propagation is highly likely.

7.2 Evaluation of Failure Types

A convenient tool for identifying specific events leading to fatigue failure is a fault tree [16]. This is a common tool in reliability analysis which has potential as a means of distinguishing failure types within a given class. From the fault tree given in Fig. 7 it is a relatively simple task to determine the "failure types" to be examined. Depending on the level of sophistication used in completing the required fault tree these failures will be identifiable through the end states of the fault tree. The data base used to build this fault tree is the information contained in Volume 10 of the A.S.M. Handbook, as is consistent with our earlier stated objectives. This is not a complete representation of the fatigue mechanism, but only a structured form of the assumed experience base. However, it can be seen from this structure how new mechanisms can be added as they are revealed by further experience, simply by developing the branches to accommodate these new events. It should be noted that this structured approach is not strictly necessary with a data base of this size, since an exhaustive search can be achieved reasonably effectively by a direct scan. However, the situation is likely to change significantly if the data base grows to tens or even hundreds of thousands.

Since initiation is the dominant phase of fatigue, any event which accelerates or eliminates this phase, will effectively cause failure. It is not necessarily true that the presence of quench cracking, or rolling laps can be equated with component failure under all circumstances, but in this example, given the expected service conditions, these defects are critical. Their presence is equivalent to failure, and for conciseness will be referred to as such from here on in this paper.

7.3 Evaluation of Failure Elements

Each failure type is broken down into elementary components that are essential to the occurrence of the failure. This involves breaking down the failure type into basic elements to form what is known as a Material Failure Logic Model (MFLM). These elements identify the logical combination of process parameters which must be satisfied if failure is to be possible by the mechanism under consideration. In Fig. 8 the failure mechanism of decarburization is shown broken down into its component elements, ready to be used in the failure matching portion of the analysis.

It should be noted that no reference has been made in the first three stages of the analysis to the type of component under consideration. Therefore, these "failure elements" are independent of component type, and based solely on the failure mechanism itself. This fact lends itself to a formal system of failure analysis, and will be discussed later.

7.4 Failure Mechanism Search Procedure

Once the MFLM's have been determined a comparison, or "failure match", can be made between these logic models and any manufacturing process, firstly to determine the existence or otherwise of the failure mechanism in the process, and secondly the critical operations and parameters which will cause that mechanism. In Fig. 9 a simple production flow diagram of the part under consideration (a truck leaf spring) is shown. It is recognized that the amount of information shown is minimal. This is a disadvantage, but the nature of the search is such that this only means that some failure mechanisms will be considered which would be excluded if more information were available. Having reviewed the search process in principle the following section discusses the results in the current example.

8. FAILURE SEARCH RESULTS

To aid in the evaluation of the search results feasible failure mechanisms were grouped under the following error classifications.

1. Inherent Failures
   - A. Single Failure due to an Erroneous Choice of an Individual Process
   - B. System Failure due to an Erroneous Choice of a Combination of Processes
2. Process Errors
   - A. Material Substitution
   - B. Process Deviation
   - C. Process Repetition and Process Omission
   - D. Spurious Processes
   - E. Bizarre Failures

Each of the above error classifications will be described in detail below, and the feasible MFLM's (relating to the spring problem) which fall into each classification will be identified and discussed. Each classification is discussed under four subheadings.

1. Conditions For Failure - Generic MFLM description.
2. Result - Material degradation resulting from the occurrence of an MFLM.
3. Consequence - Effect on fatigue resistance resulting from the occurrence of an MFLM.
4. Relation To Specific Process - Relation of MFLM's to the production of a truck leaf spring.

The first three subheadings relate to a generic failure type which may be referred to several times in different contexts. For this reason details are deferred to Appendix B. The final subheading places the generic model in the context of the specific process under consideration.

8.1 Inherent Failures

Inherent failures are failures whose elements are basic to the process as planned. This problem is often caused by division of responsibility so that noone sees the whole process.

8.1.1 Individual Process

In this group four failure mechanisms are possible according to the fault tree.

Decarburization I

Fretting I

Initial Crack-like Defects

Forming Process Induced Crack-like Defects

Decarburization I - Heating to elevated temperatures in the presence of an oxidizing atmosphere. (See Model B1 - Appendix B).

Relation To Specific Process - The material is appropriate to the decarburization model; from the production flow diagram time is spent at high temperatures, typical of decarburization; there is no indication of a controlled cover gas; therefore, until evidence to the contrary is provided, it must be assumed that the process is carried out in air. All elements of the mechanism are present, or can be assumed to be present.

Fretting I - Cyclic, relative motion of extremely small amplitude between two tight-fitting surfaces [13]. (See Model B2 - Appendix B).

Relation To Specific Process - In the process "assemble leaves" two components are placed into contact which have the possibility of moving relative to one another, thereby providing the conditions necessary to obtain fretting. Under normal circumstances the interfacial stresses are small, therefore fretting is unlikely, but current understanding of fretting does not exclude the phenomenon for any threshold level, so the mechanism remains as a logical possibility until proven otherwise. (Current understanding is taken from references [1,13]).

Initial Crack-like Defects - Procurement of a stock material with preexisting crack-like defects. (See Model B3 - Appendix B).

Relation To Specific Process - In procurement the presence of preexisting defects must be recognized. There are numerous precedents for initial defects in material as supplied. Unless it can be guaranteed that all incoming material can be examined with 100% effectiveness it is possible to have defects from this source. (Note that, in the case of high-cycle fatigue any initial crack-like defect is significant, therefore size is not a major issue in this case (see Appendix A for this analysis)). The spring manufacturer will only be able to control the introduction of these defects indirectly, through material specifications, so that these defects must be recognized as a potential problem area.

Forming Process Induced Crack-like Defects - Component processing steps of grinding, shearing, and forming, provide potential sources of defects. (See Model B4 - Appendix B).

Relation To Specific Process - The product flow diagram shows shearing, grinding, and rolling operations, which are potential sources of crack-like defects, if performed in an uncontrolled manner. The basic mechanisms of crack formation are not relevant at this point.

8.1.2 Combination of Processes

Although processes may be individually acceptable their combination can sometimes lead to failure because individual processes may interact in a deleterious manner.

Decarburization II

Decarburization II - Exposure to elevated temperatures for an extended period of time. (See Model B1 - Appendix B).

Relation To Specific Process - From the product flow diagram it is seen that the requirement for extended time at temperature is satisfied due to the large number of processes performed between heating the specimen to roll tapers (1090°C) and positioning the leaf in the camber dies. It should be noted that this mechanism is due to the cumulative effect of a number of processes which individually may perform satisfactorily. Therefore, in attempting to eliminate this failure mechanism it must be ensured that the maximum cumulative loss of carbon resulting from the above specified processing steps is below a specified critical value.

8.2 Process Error Failures

The second group consists of failures resulting from process errors. In this situation process errors are not simply taken to mean variations within normal statistical control, but fundamental deviations from the nominal process.

8.2.1 Material Substitution

The prediction of failures due to material substitutions would at first glance seem to be an overwhelming problem due to the numerous possibilities that could be substituted in any given situation. If one takes a comprehensive overview of the process under consideration it will be found that the system itself will inherently prohibit the use of a great number of materials, thus reducing the possible substitutions to a manageable number. In the present situation any materials that are not ferrous-metalic (such as copper, plastics, etc.) would be readily rejected during a visual inspection of the material. Substitution of material without the same strength and hardening capabilities of the specified material should be evident during the bulldozing operation due to its significantly different behavior from the expected. However, unless the bulldozing operation is deliberately configured as a controlling process, any ferritic material is logically acceptable as a substitution.

Strain Age Embrittlement

Strain Age Embrittlement - Delayed embrittlement and localized cracking of a susceptible material, following a critical degree of cold work. (See Model B5 - Appendix B).

Relation To Specific Process - The second shot peening operation and the bulldozing operation (which supply plastic deformation) are not followed by any further heat treatments. Therefore, if a material susceptible to strain age embrittlement (such as rimmed or semi-killed steel) is substituted for the (non-susceptible) material specified, strain age embrittlement can occur.

NOTE: An interesting question in the area of material substitution is whether a substituted material that causes no detrimental effects is considered a failure. If one chose to include cost considerations in the failure analysis then such a substitution could reasonably be considered a failure, if a more costly material was used in error. Since the basic concern of this study lies in producing a functional component the mere act of material substitution is not considered a failure, per se.

8.2.2 Process Deviations

In determining these errors the individual processes are allowed to vary as much as was necessary to cause failure. By this consideration seven types of failure possibilities were found.

Instantaneous Quench Cracking

Delayed Quench Cracking

Incomplete Martensite

Retained Martensite

Fretting II

Retained Ferrite

Loss Of Residual Stress State

Instantaneous Quench Cracking - Non-uniform rapid cooling of a material. (See Model B6 - Appendix B).

Relation To Specific Process - It is possible that the material supplied is susceptible, since it is fully hardenable; the conditions of rough surface and sharp edges are satisfied by the finish and edge likely to be produced during shearing and forming; and quenching is specified as part of the process. Therefore, quench cracking by this mechanism is logically feasible.

Delayed Quench Cracking - Uniform, rapid cooling (usually by quenching) followed by a time delay and then subsequent tempering. (See Model B7 - Appendix B).

Relation To Specific Process - The conditions exist for the same reasons that apply for instantaneous quench cracking, as described above.

Incomplete Martensite - If the final quench temperature is too high austenite is retained. (See Model B8 - Appendix B).

Relation To Specific Process - The material is fully hardenable and quenching is a normal component of the process. Therefore, this mechanism is feasible if the quench medium is held at too high a temperature or if the component is removed from the quench too soon and allowed to reach an equilibrium temperature which is too high, before cooling to ambient temperature in air.

Retained Martensite - Insufficient tempering of a material with a martensitic microstructure. (See Model B9 - Appendix B).

Relation To Specific Process - In the process under consideration a quenching process is performed which results in the formation of martensite. A subsequent tempering process is then performed in order to remove the martensitic microstructure. If proper control is not maintained on the tempering process, namely that the tempering temperature is not too low, and that the duration of the temper is not to short, a hard, brittle, martensitic structure will remain.

Fretting II - Cyclic, relative motion of extremely small amplitude between two tight-fitting surfaces [13]. (See Model B2 - Appendix B).

Relation To Specific Process - Fretting is logically possible, but unlikely under normal circumstances. However, if high spots are produced on the contacting surfaces by shear lips, surface irregularities (such as differences in curvature), or trapped particles, then this mechanism becomes highly probable (Fig. 10).

Retained Ferrite - Incomplete austenization during heat treatment. (See Model B10 - Appendix B).

<u>Relation To Specific Process</u> - Austenization followed by quenching and tempering are part of the normal specified process, therefore, a single error in the austenization temperature is sufficient to induce the required failure conditions.

<u>Loss Of Residual Stress State</u>

Residual compressive stress induced in the surface is a necessary requirement of the design to suppress fatigue crack initiation. If the shot peening operation is incomplete or insufficiently intense the necessary level of compressive stress will not be achieved.

8.2.3 Process Repetition and Process Omission

Although these are two distinct categories it is convenient to discuss them together. Ideally, to identify precisely which processes are critical in regard to process repetition or process omission, further information is required concerning the processing operation layout of the plant. Without this additional information it is possible to postulate many events which actually are not sensible. Within the framework of the information given however it is possible to draw some sensible conclusions, regarding likely failure possibilities, which can be used to focus subsequent data collection efforts.

Though all processes are potential candidates for being repeated or omitted, either totally or partially, any process involving shape changes cannot be repeated or omitted without immediate detection at the point of entry to the next process. The only processes therefore which need to be considered are those which involve transformations of the material state without accompanying geometrical changes. By these considerations the following operations need to be considered in regard to process repetition and process omission.

1. Heat Treatment (870°C)
2. Agitated Oil Quench (70°C)
3. Furnace Temper (480°C for 45 to 60 min.)
4. Stress Peen

Effects of Repetition

Heat Treatment, Quench, Temper - The repeat of any part of the sequence, such as double tempering, is likely to lead to significant deterioration of material properties to such an extent that repetition is almost certainly unacceptable. In each case of repetition it is possible to identify several detrimental effects, which do not need to be detailed here.

Stress Peen - Repeated stress peening could give rise to an overhardened surface layer in the component, resulting in excessively high (detrimental) hardness gradients.

Effects of Omission

Heat Treatment, Quench, Temper, Stress Peen - Total, or partial, omission of any of the above processes would almost certainly produce a microstructure with unsatisfactory fatigue properties.

It is almost self evident that the operations listed above are critical to the integrity of the component, and that the likelihood of omission is small. However, at this stage of the analysis we are only investigating occurrences that lead to the possibility of failure, and experience shows that failure resulting from process repetition and process omission have been known to occur. When additional information is obtained regarding the plant layout these possibilities can be evaluated more thoroughly.

8.2.4 Spurious Processes

Spurious processes include those which are not specifically part of the production cycle of the component. These processes can occur due to a number of reasons. For instance, in the present example the application of a severe heat source to a properly constructed and installed leaf spring could cause an inferior microstructure and accelerated fatigue. This heat source may occur, for example, by inadvertent heating from a torch while performing work on another portion of the vehicle. Some further examples are listed in Table 3. As can be seen, spurious events tend to occur in repair or operation circumstances. It is impossible to list all spurious process, but it is possible to classify the detrimental results of such process, so that they can be identifiable by inspection. There are two basic categories, geometric and metallurgical.

1. Geometrical Errors - Gross shape changes are unlikely to propagate any distance through the system, and so can be ignored. The most likely effects of a spurious process are surface damage in the form of notches, caused by impact, and entrapping of foreign particles between contacting surfaces.
2. Metallurgical Errors - The only practical means of obtaining the modified microstructure, without changing the shape, is by some spurious heating cycle.

8.2.5 Bizarre Failures

Bizarre failures can not reasonably be foreseen or predicted, regardless of the type of analysis that is performed. For instance, as an example, liquid embrittlement has been known to result from coated nail heads falling from a deteriorating roof structure onto a conveyor belt carrying stainless steel components through a heat treatment process. This source of contamination would be very difficult to anticipate without prior example. Examples are more common in site installations, such as the relief valve installed with the blanking plates, used to protect the internals in transit, still in place, or the complete welding set left inside the main pump housing of a boiling water reactor. (These incidents were taken from USNRC Licensing Event Reports [17]). Though it is recognized by the authors that this type of failure is possible, through this exercise it has been found that the number of failures that could be considered bizarre (due to being non-predictable) is very small indeed. It is recalled that of the 125 case studies mentioned by ASM (given in Table 1) none could be considered as a bizarre occurrence. Even though it is realized that bizarre failures will inevitably occur, and that no amount of analysis can predict, and therefore eliminate, these failures, it was found that through the use of this design strategy that failures which at first glance appeared to be nonpredictable are found upon further analysis not only to be predictable but to be reoccurring as well.

8.3 Summary of Classified Failures

The failure mechanism possibilities that were obtained can now be summarized by classification under the previously mentioned failure headings. The failure possibilities found, shown listed under the proper classification headings, are given in Table 4.

9. PRESENTATION OF FAILURE SEARCH RESULTS

Once the potential modes of failure have been identified a means of presenting the information is required which provides a good visual insight as to the most critical processes of the production cycle. One such method is shown in Fig. 11. In this figure a check list compares the manufacturing processes to the failure mechanism possibilities. This check list gives a good indication of the critical operations in the production of the component. Not all the process steps listed can be modified or controlled so as to eliminate the MFLM's to which they contribute. For instance, an essential event in the strain aging MFLM is plastic deformation, which in this case is provided by the stress peening and bulldozing operations, and is a necessary part of the normal manufacturing process. To eliminate this MFLM, therefore, one must address the other elements of the logic sequence. Applying this approach to all identified MFLM's it is possible to identify which processes are available for modification as a means of failure prevention. This reduced set is given in Fig. 12.

Once this revised check list has been obtained further analysis can be centered on the individual parameters of each process which contributes to a possible failure of the component. For instance, it is shown that the quenching process is critical in three different failure possibilities. From the failure search results the critical parameters in the quenching operation for each of these failure possibilities were determined. Therefore, a listing can be made of the important parameters in the quenching process in regard to a specific set of failure possibilities. If this procedure is repeated for all of the processes present a list of critical parameters is obtained, as shown in Table 5 for the example process presently under consideration. At this point a listing has been developed which indicates the areas in which further analysis and preventive action need to be applied in order to eliminate the previously indicated failure possibilities.

10. PREVENTIVE ACTION ARISING FROM FAILURE MODE ANALYSIS

The failure mechanisms identified in the previous section have only been established as logical possibilities. This does not necessarily mean that they are certain to occur if no remedial action is taken. Strictly, therefore, the next stage in the analysis should be to determine the likelihood of each mechanism, by some form of quantitative analysis, before deciding on the need for preventive action. In practice however it is often possible to make final decisions without recourse to further quantitative analysis. In many cases for instance, once a potential failure has been identified, the task of breaking the logic sequence can be achieved by a relatively simple modification of the production process, in which case it is easier to eliminate the problem completely than to try to evaluate it further. This is an action which can often be justified by the fact that gross deviations do not show constant patterns of variability. The fact that there has been a gross error is usually sufficient evidence to believe that unacceptable material degradation has occurred. In other cases, strain age embrittlement being one, there is insufficient quantitative information available on the subject to allow further evaluation to be carried out with any confidence. In such a situation several alternative actions are possible. The logic sequence can be broken as before, on the assumption that the worst case is likely. Alternatively, tests or inspections specifically designed to determine whether a critical state of deterioration is achieved can be carried out.

From the Failure Search Results the critical process parameters in regard to failure by accelerated fatigue were obtained. This information can be used to identify those portions of the general quality control program which require extra surveillance in order to prevent failure by material degradation.

It is realized that past experience will provide a good source of information in regard to the control of various parameters. Where adequate experience provides evidence showing that a suspected failure mechanism does not in fact occur under the given conditions then the mechanism can be ignored. However, care must be taken to ensure that the current situation is similar to past experience. What will be presented below are those actions that are required if no past experience is available on which to draw upon.

Decarburization I

If no cover gas is provided:

1. A test would need to be made to determine whether heat treatment in an uncontrolled environment is likely to produce a critical amount of decarburization.
2. If decarburization is excessive a suitable cover gas must be provided.

If a cover gas is provided:

1. Special attention needs to be given to the upper and lower limits on the carburizing potential.

Fretting I

1. An approximate analysis needs to be carried out to determine whether the qualitative conditions required for fretting are likely to be satisfied.
2. If necessary, a test should be performed to determine the exact conditions under which fretting would occur.

Initial Crack-like Defects

From prior analysis a crack of any size is significant. The only way to eliminate all cracks is by 100% inspection. In a mass produced component this is not practical, and even if it were such an inspection would not be totally reliable. It must be concluded that there is no direct method currently available to ensure freedom of failure from this source. This is, therefore, an unresolved problem. The fact that failures caused by this mechanism are actually very infrequent allows us to deduce that defects of this nature are also very infrequent, but we have no direct control over their occurrence, unless production of the stock material is included in the analysis.

Forming Process Induced Crack-like Defects

1. The specific methods of performing the shearing, grinding, and forming processes need to be checked to determine the tendency of producing cracks under normal operating conditions.
2. The operations need to be analyzed to identify opportunities for extreme operation (e.g. excessive grinding force applied, etc.), and these conditions investigated for their crack producing tendencies. If such tendencies exist, then the operating procedures must be formalized to control these specific modes of operation.

Decarburization II

The likelihood of excessive decarburization resulting from the succession of heating operations shown in the process flow diagram (Fig. 9), needs to be tested. A possible control would be a maximum total time allowed for all the heating operations. Alternatively, if one or more of these processes dominate the decarburization process control should be placed on those processes. If decarburization is likely to be excessive consideration should be given to recarburization as an intermediate step. The most effective remedy would be to perform the final heat treatment in a compensating carburizing atmosphere.

Strain Age Embrittlement

1. Since Strain Age Embrittlement is only reasonable in the event of a substitution a task analysis on the procedure for material procurement and transfer would be necessary to determine the possibility and likelihood of material substitutions.
2. On a more general level it is possible to use the final bulldozing operation as a control procedure by monitoring the load at which permanent set is achieved. This would automatically identify any material substitutions which would result in material strength either significantly higher or lower than that of the specified material. Since strain age embrittlement is largely a phenomenon in low carbon steels this substitution would be detected by its low strength characteristics.

Instantaneous Quench Cracking

1. Inspection and removal of all burrs and rough edges should be specified. In addition, a minimum rate should be specified for emersion in the quenching medium. For preference the part should be emersed horizontally in order to produce as uniform a quench as possible over the entire surface of the part.
2. Control should be maintained on the minimum temperature of the quenching medium to ensure that it does not drop too low.

Delayed Quench Cracking

This problem can be avoided by ensuring that the duration of the transfer period between the quenching and tempering processes is not too great.

Incomplete Martensite

This problem can be avoided by ensuring that the maximum temperature of the quench medium is not excessive, and the duration of the quench is not too short.

Retained Martensite

By ensuring that the tempering temperature is not too low and the tempering duration is not too short this possible means of failure can be eliminated.

Fretting II

The maximum geometric incongruency between the mating surfaces of the spring must be controlled to eliminate this possible means of failure.

Retained Ferrite

This failure possibility can be avoided by ensuring that the duration of the heat treatment process is not too short and the temperature at which the heat treatment process is carried out is not too low.

Loss Of Residual Stress State

Procedures for stress peening need to be reviewed to ensure that a complete coverage of the spring surface is achieved. In particular, emphasis needs to be placed on the central section of the spring on its upper surface, and on edges and holes.

The failure control scheme outlined above is not expected to be a final plan. The object of the analysis carried out up to this point is to identify parameter variations of real concern so that surveillance effort can be focused on these, instead of being dissipated in areas of no concern. In practice the needs would probably change as more information about the process is collected. For instance, the specification of control over the cover gas during heat treatment could be redundant because the process may already be carried out in this manner. The failure control program would then have to be modified to include error states such as loss-of-cover gas, loss-of-control-of-carburizing-potential, etc. However, a control program developed from a preliminary or simplified model of the production process is broader than a program devised from a more detailed model. The only changes resulting from more information are that preventive actions are focused on greater detail, or on more subtle aspects of the process. The important point is that new failure mechanisms are not revealed by going to greater detail. On the contrary, it is expected that possibilities considered at a preliminary level will be excluded from further consideration as the depth of detail increases. The strategy is, therefore, inherently conservative.

Summarizing this section it may be concluded that logical failure conditions, while not sufficient to ensure failure, are powerful tools for planning preventive action. It is possible to develop a reasonably effective control program for a given product by using the information contained in these conditions alone. The strategy applied to each failure mechanism in turn is to find the easiest point at which the MFLM logic sequence can be broken, and to make a cut at this point. The precise form of the cut depends on the circumstances, in some instances requiring changes in the actual process, while in others being limited to a narrowly prescribed surveillance activity with a very specific objective. Superimposing the MFLM's on the production flow diagram, as shown in the previous section in the form of a check list, is a useful technique for identifying steps (operations) where the least amount of modification to the production cycle can have a maximum effect. It appears to be a characteristic of many production processes that a few critical steps are common to the majority of potential failure mechanisms. Furthermore, each of these critical steps (operations) may be composed of a number of critical parameters. For instance, in the quenching operation of the present example the minimum and maximum quench medium temperature, the rate and duration of the quench, and the duration of the transfer period following the quenching operation (proceeding tempering) are all critical parameters (Table 5). This information, concerning the criticality of parameters, can then be used to determine a list of suggested actions which can be used to prevent potential failures.

11. EFFECTS ON THE SCOPE OF DESIGN

In any major engineering activity design already carries a heavy burden of responsibility covering a wide spectrum of expertise. The type of analysis presented here requires that spectrum to be expanded to include a fairly detailed understanding of manufacturing processes, quality control procedures, and material behavior. Furthermore, this breadth of knowledge must be born by an individual, or at least a small, closely knit group, in order to maintain a complete picture of the product development cycle. Specialism within the design organization merely copies on a different scale the knowledge fragmentation problem which contributes to the cause of failures at present. A technical problem arises though regarding how the depth and breadth of knowledge required for design can be increased simultaneously.

In fact the task is not as difficult as it appears at first glance as long as the problem is tackled from the top down, i.e. the product development cycle is modeled completely, but superficially to start with, but with increasingly more detail in successive iterations. Despite the fact that the actual volume of knowledge required in any given application is relatively small, it is necessary to acquire a certain form of sophistication regarding selective acquisition and subsequent discarding of information in order to perform this type of analysis. The traditional teacher in the past has been experience, and it is believed to be the engineers with a reasonable breadth of knowledge of materials, processes, and service conditions who should be capable of using the outlined strategy effectively. However, this is an informally structured capability which is difficult to pass on in training, and is subject to the uncertainties of human unreliability. For this reason it is desirable, and it turns out to be feasible, to organize the task of process and failure mechanism descriptions, along with the search process, so that an assessment can be performed more formally using a computer based system.

The organizational structure of such a system is shown in Fig. 13. Essential features of this system are:

1. A data base containing material processing information, which is added to form continuing experience.
2. A model building module combined with a search routine.
3. An input facility to be used by experts and others to add to the data base.
4. A second, independent interface for the designer which allows interactive model building at a high level, while automatically keeping track of detailed aspects of physical modeling at a lower level.

This is in effect an "expert system", that is, one which extracts knowledge from the experience of one group of individuals and holds it selectively available for use by some second group. More commonly the title "expert system" is used to describe systems in the field of artificial intelligence which deduce knowledge structures from relatively high levels of interrogation of human experts who may have, at most, only an intuitive understanding of the source of their own expertise. In the present application there is no need to deduce the logical structure of knowledge because this can invariably be constructed directly from well understood physical principles which constitute the current state-of-the-art in engineering science. However, the basic principle underlying the use of the system is essentially unchanged in that it provides an unexperienced user with selective knowledge captured from the experience of others. To this extent the title "expert system" is justified and will be used in the future.

The task of constructing an expert system is not a simple one and will not be addressed in this paper. Such a system, called FERRET, is being developed at the University of Illinois [10,11,12]. This system was initiated by the observation of constant logical structures being displayed by failures resulting from material deterioration, leading to the concept of Material Failure Logic Models (MFLM's), which were used indirectly in this study.

12. CONCLUSIONS

1. Failures have been identified as arising from two causes, expected design conditions and error induced mechanisms. It has been shown by reference to service experience that the error induced mechanisms are a major problem which does not appear to be covered by current design practice.
2. An important area which has been relatively underrated in design are gross errors in manufacturing, such as outliers and rogue events.
3. A strategy has been developed for systematic identification of failures caused by error induced material deterioration and has been demonstrated by application to a problem involving the manufacture of a vehicle leaf spring.
4. It has been shown that logical descriptions of material failure mechanisms (MFLM's) are a useful device for rapidly identifying critical process steps and providing a structure on which rational preventive action may be built.
5. The example shows that an apparently very extensive search problem involving many possible failure events can be reduced to a small, manageable number, once the manufacturing process and purpose of the component has been defined, even approximately. Therefore, the proposed strategy is a potentially useful design aid.
6. Within a given experience base the strategy outlined is expected to overestimate the potential for failure by including failure mechanisms which would be rejected if additional information were available. This means that the procedure is an inherently conservative one.

7. A consequence of the failure assessment strategy is that those aspects of quality control which relate directly to the potential for failure of the component, given its specific service requirements, can be distinguished from those quality control activities which are required simply on the basis of good practice.

APPENDIX A

Although no details are given of the spring construction, it is possible to draw some conclusions about the likely fatigue problem areas, using only the knowledge of its eventual application and its nominal strength as quoted by Landgraf [14].

From Rolfe and Barsom [15], the crack growth rate for martensitic steel is

$$\frac{da}{dN}\ (\mathrm{mm}) = 1.807\mathrm{E}{-10}\ [dk(\mathrm{MPa}(m)^{1/2})]^{2.25}.$$

This equation can be readily integrated to give the following relation for cycles to failure.

$$N = \frac{8}{a_0^{0.125} * C * (pi)^{1.125} * (\Delta\sigma)^{2.25}}.$$

Where

a_0 = Original crack size

C = 1.807E-10

$\Delta\sigma$ = Stress range in MPa.

It can be seen that once there is an initial defect in this material, fatigue life does not depend very strongly on the size of the defect. Table A.1 shows that regardless of the crack size, the remaining life is only about 1E + 5 cycles at a stress range of 500 MPa. This corresponds to one very modest load cycle, about 0.15 of the elastic range for the material, every mile travelled. Even without any further knowledge of the service conditions it can be deduced that these conditions would represent an exceptionally conservative design. It is reasonable to assume that the actual stress cycle will be more severe than assumed here. This means that an initial crack-like defect of only a small fraction of a mm will cause premature fatigue failure. For this reason, it is considered that an initial crack of any size is a feasible failure mechanism for this particular problem.

TABLE A.1

Crack Size (mm)	Stress Range (MPa)	Failure Cycles (N)
1.0	1000	2.2E + 3
	500	1.0E + 4
	300	3.3E + 4
	100	3.9E + 5
0.1	1000	2.9E + 3
	500	1.4E + 4
	300	4.3E + 4
	100	5.2E + 5
0.01	1000	3.9E + 3
	500	1.8E + 4
	300	5.8E + 4
	100	6.9E + 5

APPENDIX B Mechanisms Contributing To Accelerated Fatigue

B1. Decarburization

Conditions For Failure - (steel with free carbon as a hardening agent) and (high temperature) for ((an arbitrary period of time) subjected to (a strong oxidizing atmosphere)) -or- ((an extended period of time) subjected to (a weak oxidizing atmosphere)).

Result - Carbon loss at exposed surfaces, causing localized loss of tensile strength, a possible increase in ductility, and slight increase in surface tension due to a reduction in specific volume.

Consequence - (a) Low-cycle high-strain fatigue - Little effect on initiation time, and no major effect on crack propagation rate.

(b) High-cycle low-strain fatigue - Significant reduction in initiation time, and no major effect on crack propagation rate.

B2. Fretting

Conditions For Failure - (any two materials) in (contact) under (high interfacial pressure) subjected to (small amplitude sliding oscillation).

Result - Accelerated crack initiation by the production of microcracks and delaminations from the microscopic wear process.

Consequence - Acceleration of the crack initiation period.

B3. Initial Crack-like Defects

Conditions For Failure - (any material) containing (small crack-like defects) in (an initial state) subjected to (high-cycle low-strain fatigue conditions).

Result - Elimination of crack initiation period which, in the case of high-cycle low-strain fatigue, constitutes the major portion of the fatigue life.

Consequence - Elimination of the crack initiation period and significant reduction of life.

B4. Forming Process Induced Crack-like Defects

Ideally, the basic conditions for defect production in these processes should be related to variations in the parameters controlling the process. The current state of knowledge does not allow this to be done in a simplified way, so a simplistic model, which assumes that cracks are possible if the processes are present, will be adopted.

Conditions For Failure - (any material) and (grinding -or- shearing -or- forming operation).

Result - Elimination of the crack initiation period of the fatigue life.

Consequence - Elimination of the crack initiation period and significant reduction in life.

B5. Strain Age Embrittlement

Conditions For Failure = (low or medium carbon steel in rimmed or semi-killed condition) subjected to (plastic deformation of the order of 4% or more) followed by (an incubation period which does not contain a heat treatment of the order of 350°C or above).

Result - Increase in yield strength accompanied by a reduction in ductility and toughness, caused by the pinning up of dislocation networks by nitrogen atoms.

Consequence - If the embrittlement is localized, this leads to arrested fracture upon application of a high overload, resulting in virtual elimination of the crack initiation period.

B6. Instantaneous Quench Cracking

Conditions For Failure - (a fully hardenable steel) having (a rough finish or sharp edges) subjected to (fully austenitizing temperatures) and (an abnormally high quench rate -or- an abnormally high austenitizing temperature prior to quench -or- a non-uniform quenching emersion rate).

Result - Too rapid a transformation of surface layer leads to premature formation of martensite, which forms surface cracks when the remainder of the part undergoes volumetric expansion during the martensitic transformation.

Consequence - Elimination of the initiation phase of the fatigue life through the formation of surface cracks.

B7. Delayed Quench Cracking

Conditions For Failure = (a fully hardenable steel) subjected to (quenching from a fully austenitized condition) followed by (insufficient submersion time in quench medium before removal).

Result - Partial transformation to martensite leaves retained austenite which then transforms over an extended period of time leading to cracking of the surface layer by volumetric expansion.

Consequence - Elimination of the initiation phase of the fatigue life through the formation of surface cracks.

B8. Incomplete Martensite

Conditions For Failure = (a fully hardenable steel) subjected to (uniform quenching from a fully austenitic state in a quench medium at an abnormally high temperature -or- a non-uniform quenching followed by removal before obtaining an equilibrium state, leading to an abnormally high martensite transformation temperature) followed by (shock -or- vibration loading in service).

Result - Austenite is retained through the tempering process and subsequently is transformed to untempered martensite in service by a dynamic stress, forming a brittle phase which can crack under service loading conditions.

Consequence - Elimination of the initiation phase of the fatigue life through the formation of either surface or internal cracks.

B9. Retained Martensite

Conditions For Failure = (a fully hardenable steel) subjected to (uniform quenching from a fully austenitic state) followed by (insufficient time at tempering temperature -or- tempering at too low a temperature).

Result - Retention of brittle martensite which forms an arrested crack during subsequent loading.

Consequence - Elimination of the initiation phase of the fatigue life through the formation of either surface or internal cracks.

B10. Retained Ferrite

Conditions For Failure = (a fully hardenable steel) subjected to (heating to below the austenitic transformation temperature -or- exposure of a component to the required temperature for an insufficient time) followed by (quench and tempering).

Result - Production of an inhomogeneous microstructure of mixed low strength ferrite and high strength tempered martensite resulting in localized strain concentration or premature fatigue cracking in the ferrite.

Consequence - Accelerated fatigue crack initiation.

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TABLE 1 Summary Of 125 Case Studies

Material	Grossly substandard or out of spec.	10
	Marginally Substandard (Includes BHN errors)	3
Design Errors	Bad* or unspecified geometry	17
	Neglected load condition	11
	Wrong material choice	6
	Bad** detail design	7
Process Errors	Step omission	3
	Iteration	1
	Transposed	1
	Gross loss of process control	21
	Grossly unsuitable process	14
Operation	Different environment from expectation	5
	Damage in repair	6
Inspection	Wrong test	2
	Damage caused by NDT	2
	Failure to see gross error	2
Installation	Grossly improper or misaligned	5
	Uncontrolled procedure	1
Concealed Defects	Difficult to find	11
Multiple Causes		25
Unknown Cause		6
Possible Load Strength Interactions		6
Questionable Load Strength Interactions		6

{*} For example, a geometry which needlessly specifies sharp corners in areas of high stress or intersecting welds with no intent to post weld heat treat.

{**} For example, friction of a set-screw to transmit torque instead of a properly proportioned keyway or spline.

TABLE 2 Relevant Failure Classes

1. Elastic Deformation
2. Yielding
3. Brittle Fracture
4. Fatigue
   - A. High-cycle fatigue
   - B. Corrosion fatigue
   - C. Fretting fatigue
5. Corrosion
   - A. Galvanic corrosion
   - B. Crevice corrosion
   - C. Pitting corrosion
   - D. Intergranular corrosion
   - E. Hydrogen damage
   - F. Stress corrosion
6. Wear
   - A. Adhesive wear
   - B. Corrosive wear
   - C. Deformation wear
   - D. Fretting/wear interaction
7. Fretting
   - A. Wear/fretting interaction
   - B. Fretting corrosion

TABLE 3 Some Examples of Failures Caused by Spurious Processes

1. A large pressure vessel failed because surface undulations, resulting from the grinding out of small cracks, were considered to mar the appearance of the vessel and were built up with unnecessary and unsuitable weld rod. (Source - Confidential).
2. Stainless steel parts on an assembly line were cracked because an unauthorized brass transition piece had been put on the line to "help" the parts round a sharp bend. This led to liquid metal embrittlement cracks on subsequent heat treatment. (Source - Confidential).
3. An aluminum alloy propeller blade experienced accelerated fatigue after being bent and straightened by an unauthorized repair. (ASM Handbook [1], p115).
4. Coke oven car wheels experienced fatigue fractures from identification numbers stamped in a zone of critical stress. (ASM Handbook [1], p119).
5. Frequently repeated failures are found in the following categories,
    1. Cracking from electrical arc strikes in plating, welding, and magnetic particle testing.
    2. Unauthorized welded attachments using inappropriate welding techniques.
    3. Corrosion resulting from chemical deposits left over from unspecified clean up operations.
    4. Cracking and embrittlement caused by unauthorized grinding.

TABLE 4 Summary Of Failure Possibilities

1. Inherent Failures
    A. Individual Process
        1. Decarburization I
        2. Fretting I
        3. Initial Crack-like Defects
        4. Forming Process Induced Crack-like Defects
    B. Combination Of Processes
        1. Decarburization II
2. Process Errors
    A. Material Substitution
        1. Strain Age Embrittlement
    B. Process Deviation
        1. Instantaneous Quench Cracking
        2. Delayed Quench Cracking
        3. Incomplete Martensite
        4. Retained Martensite
        5. Fretting II
        6. Retained Ferrite
        7. Loss Of Residual Stress State
    C. Process Repetition And Process Omission
    D. Spurious Processes
    E. Bizarre Failures

TABLE 5 Critical Parameters

Process	Parameter	Accelerated Fatigue MFLM's
Material Procurement	Crack-like Defects	Initial. Crack-like Def.
	Material Type	Strain Age Embrittlement
Shear Stock	Crack-like Defects	F. P. I. Crack-like Def.
	Geometric Incongruency	Fretting II
Grind Tension Side	Crack-like Defects	F. P. I. Crack-like Def.
Heat to Roll Tapers	Cover Gas (Chem. Comp.)	Decarburization I
	Carbon Content	Decarburization II
Roll Tapers	Cover Gas (Chem. Comp.)	Decarburization I
	Crack-like Defects	F. P. I. Crack-like Def.
	Carbon Content	Decarburization II
	Geometric Incongruency	Fretting II
Trim Rolling Flash	Cover Gas (Chem. Comp.)	Decarburization I
	Carbon Content	Decarburization II
	Geometric Incongruency	Fretting II
Punch Holes For Center Bolts	Cover Gas (Chem. Comp.)	Decarburization I
	Carbon Content	Decarburization II
Heat End Of Leaf	Cover Gas (Chem. Comp.)	Decarburization I
	Carbon Content	Decarburization II
Roll Eyes	Cover Gas (Chem. Comp.)	Decarburization I
	Crack-like Defects	F. P. I. Crack-like Def.
	Carbon Content	Decarburization II
	Geometric Incongruency	Fretting II
Heat Treatment	Cover Gas (Chem. Comp.)	Decarburization I
	Carbon Content	Decarburization II
	Heat Treat. Temp.	Retained Ferrite
	Heat Treat. Duration	Retained Ferrite
Position Leaf In Camber Dies	Cover Gas (Chem. Comp.)	Decarburization I
	Carbon Content	Decarburization II
Agitated Oil Quench	Manner of Quench	Instant. Quench Cracking
	Quench Medium Temp.	Incomplete Martensite
	Quench Duration	Incomplete Martensite
Transfer Period	Duration	Delayed Quench Cracking
Furnace Temper	Tempering Temperature	Retained Martensite
	Tempering Duration	Retained Martensite
Stress Peen	Surface Compression	Loss Of Res. Stress St.

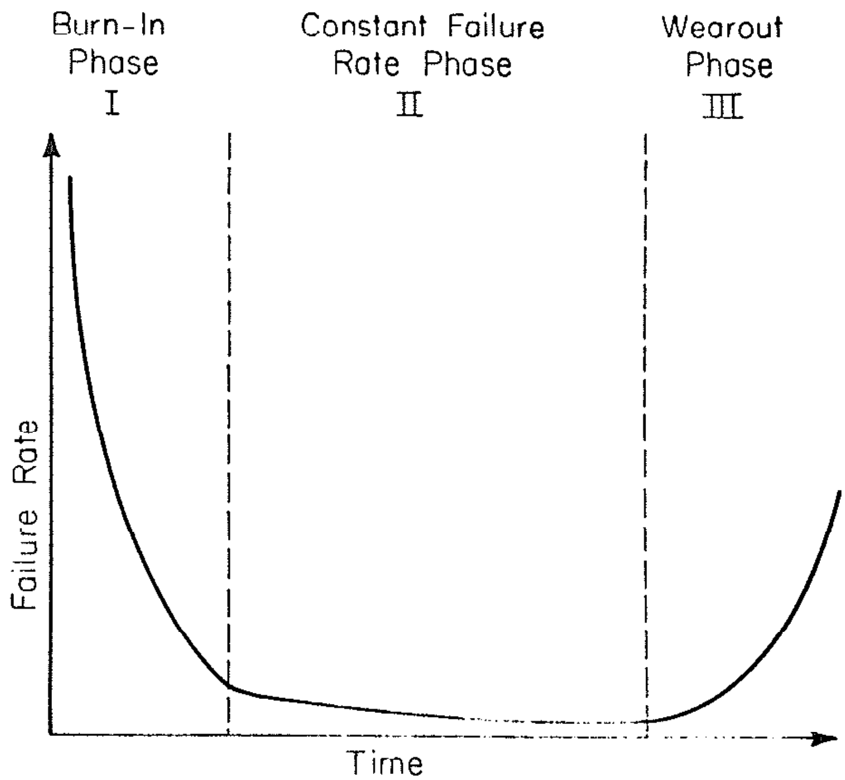


Figure 1 The Bathtub Curve.

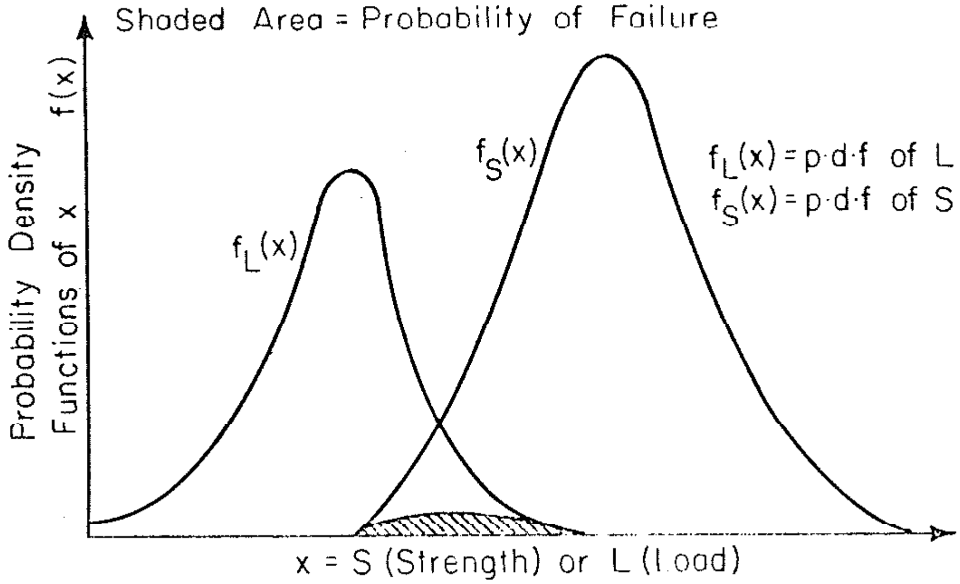


Figure 2a Conventional Load-Strength Interaction Diagram.

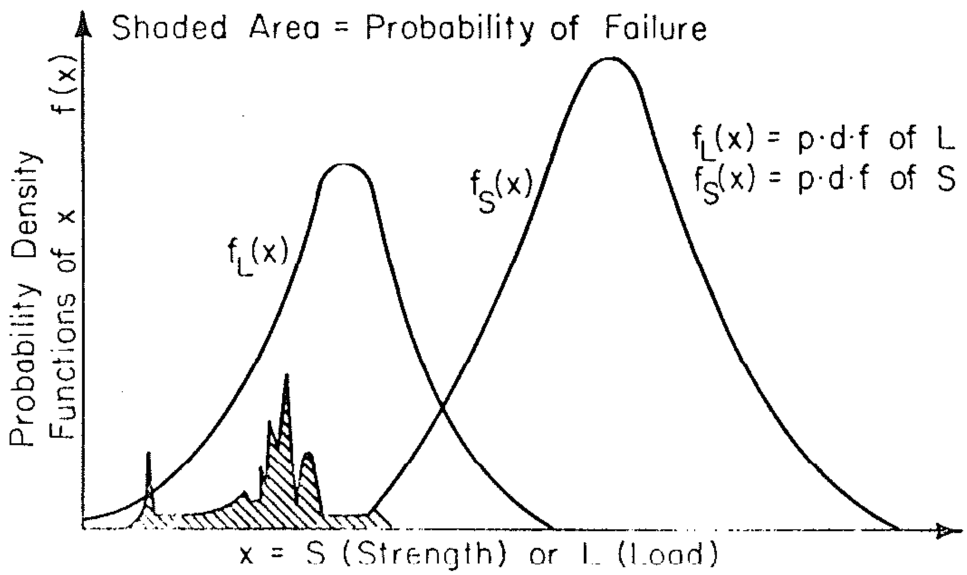


Figure 2b Multi-Tail Load-Strength Interaction Diagram.

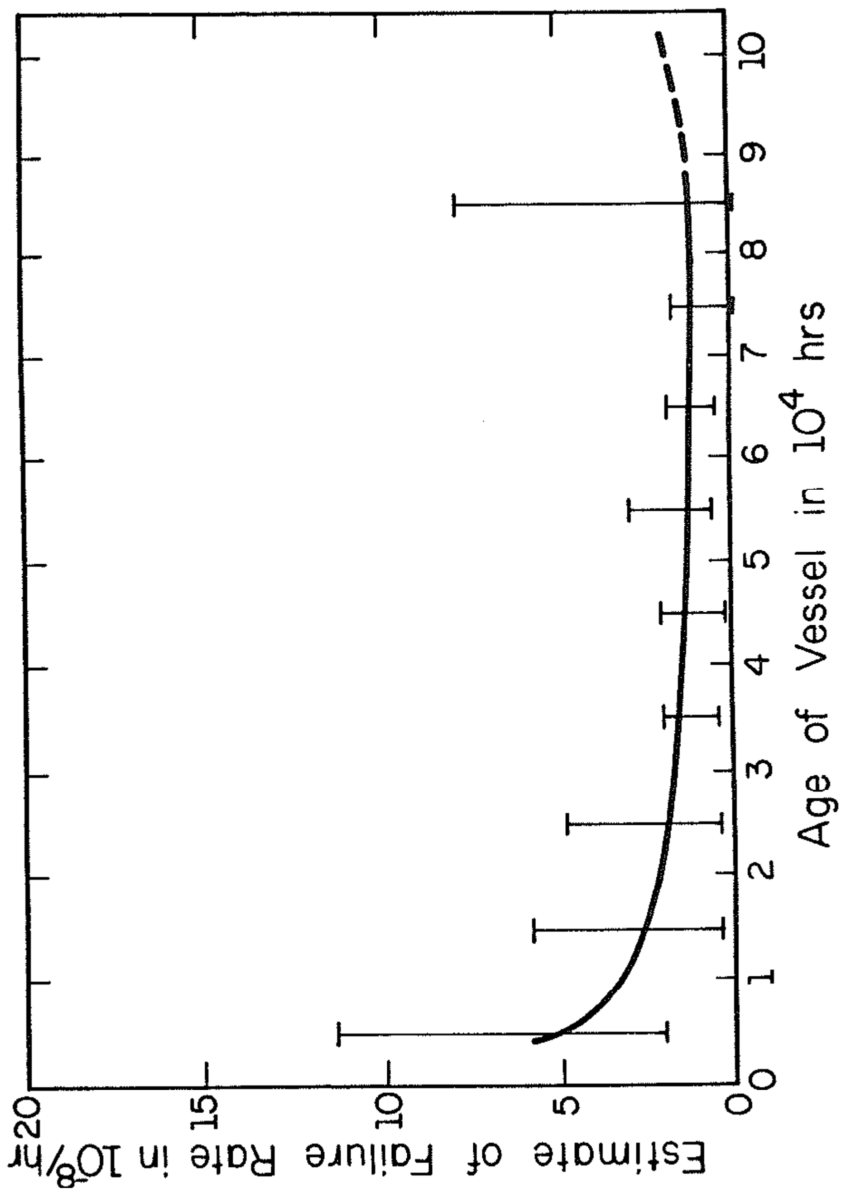


Figure 3 Hazard Rate Curve for a Class of Pressure Vessels.

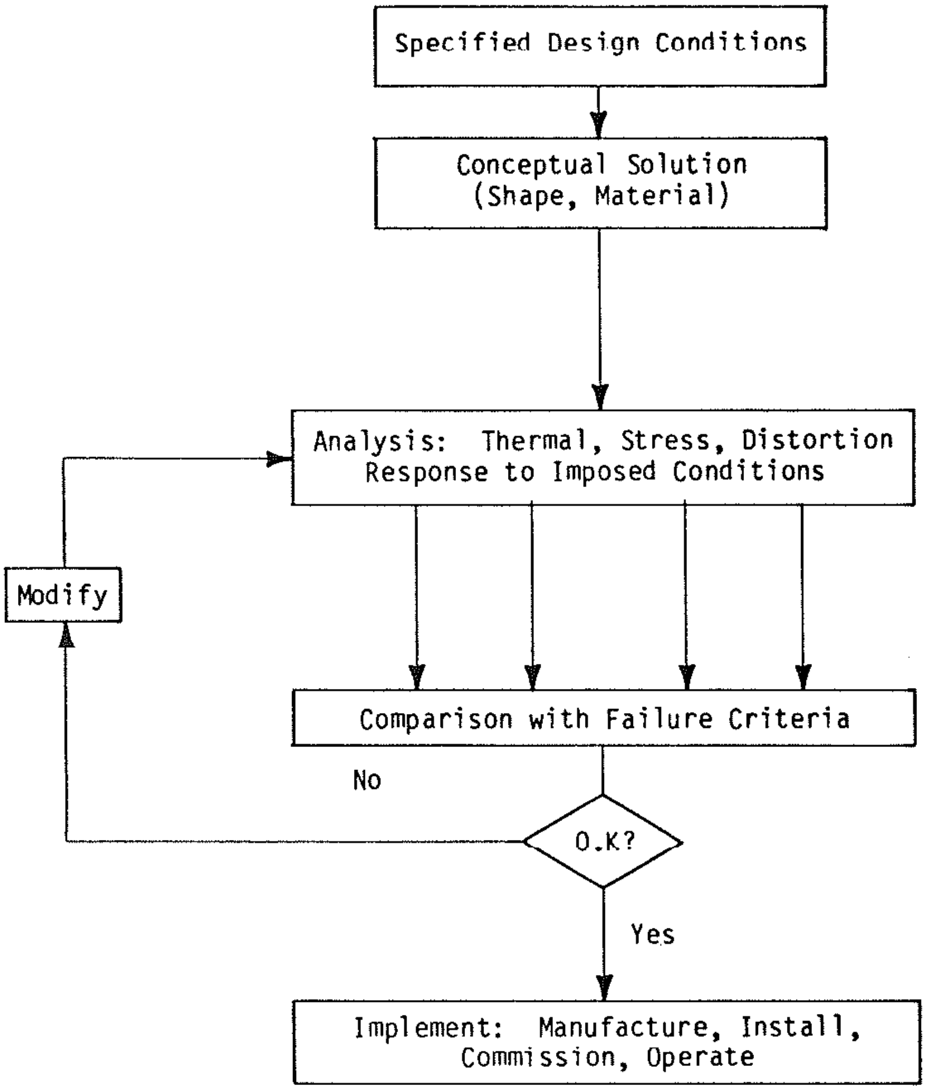


Figure 4a Flow Diagram of Typical Design Process.

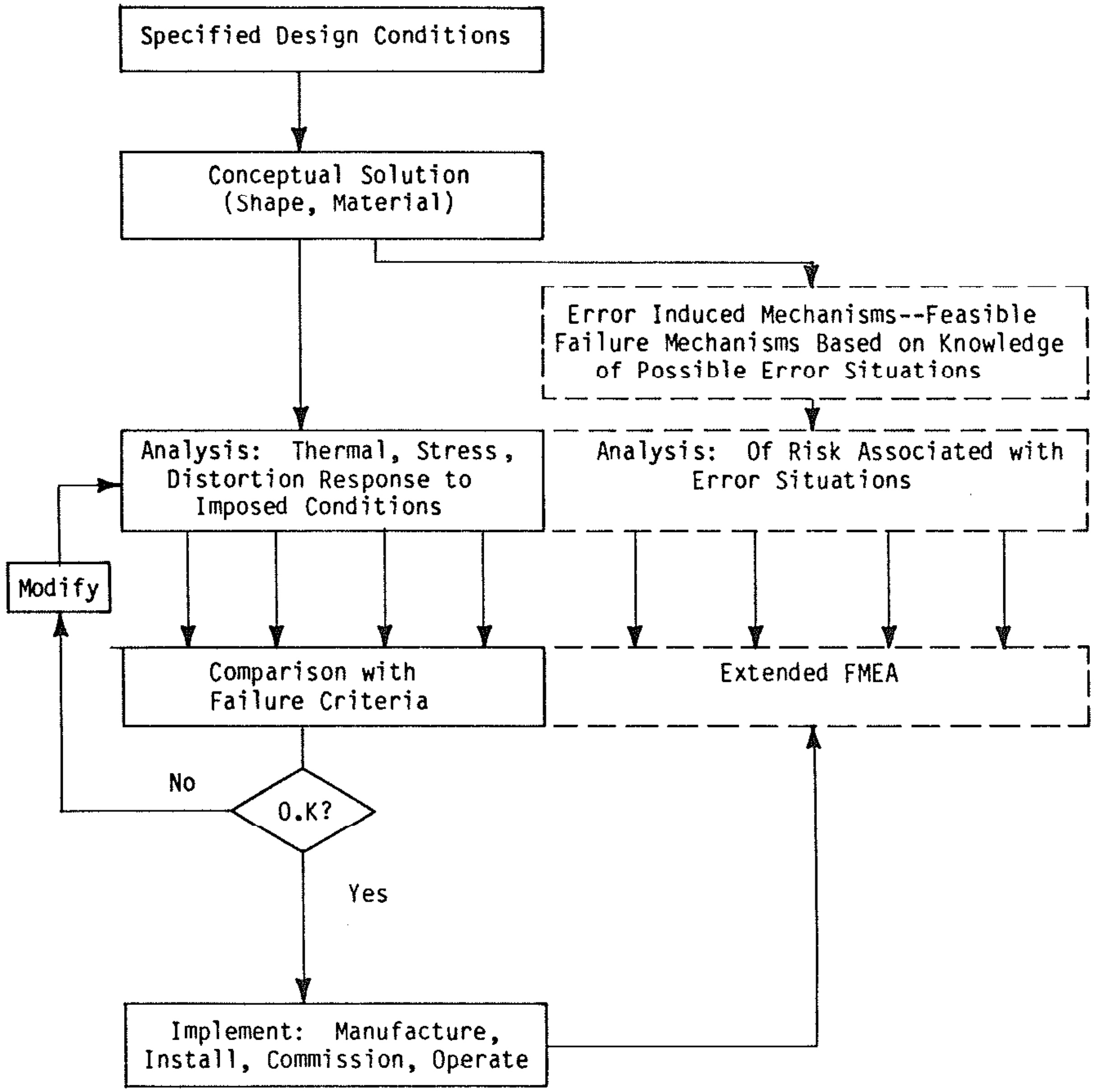
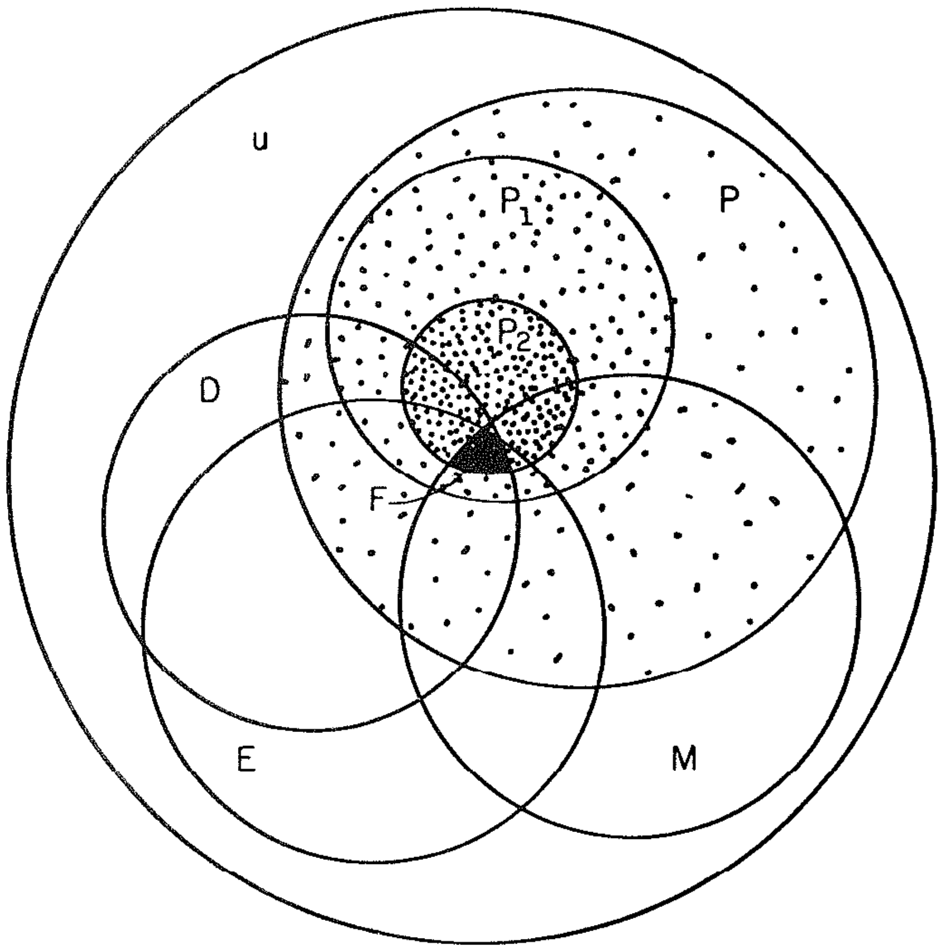


Figure 4b Modification to Design Process to Include Error Induced Failure Mechanisms.



u = Set of all Known Failure Mechanisms

M = Subset of Failure Mechanisms Constrained to Material Errors

E = Subset of Failure Mechanisms Constrained to Environmental Errors

D = Subset of Failure Mechanisms Constrained to Design Errors

P = Subset of Failure Mechanisms Constrained to Methods of Processing

P_1 = Subset of Failure Mechanisms Constrained to Forming Processes in General

P_2 = Subset of Failure Mechanisms Constrained to Rolling Processes in Particular

F = Subset of Rolling Process Failure Mechanisms with Required Error States Present

Figure 5 Venn Diagram Illustrating Progressive Application of Constraints.

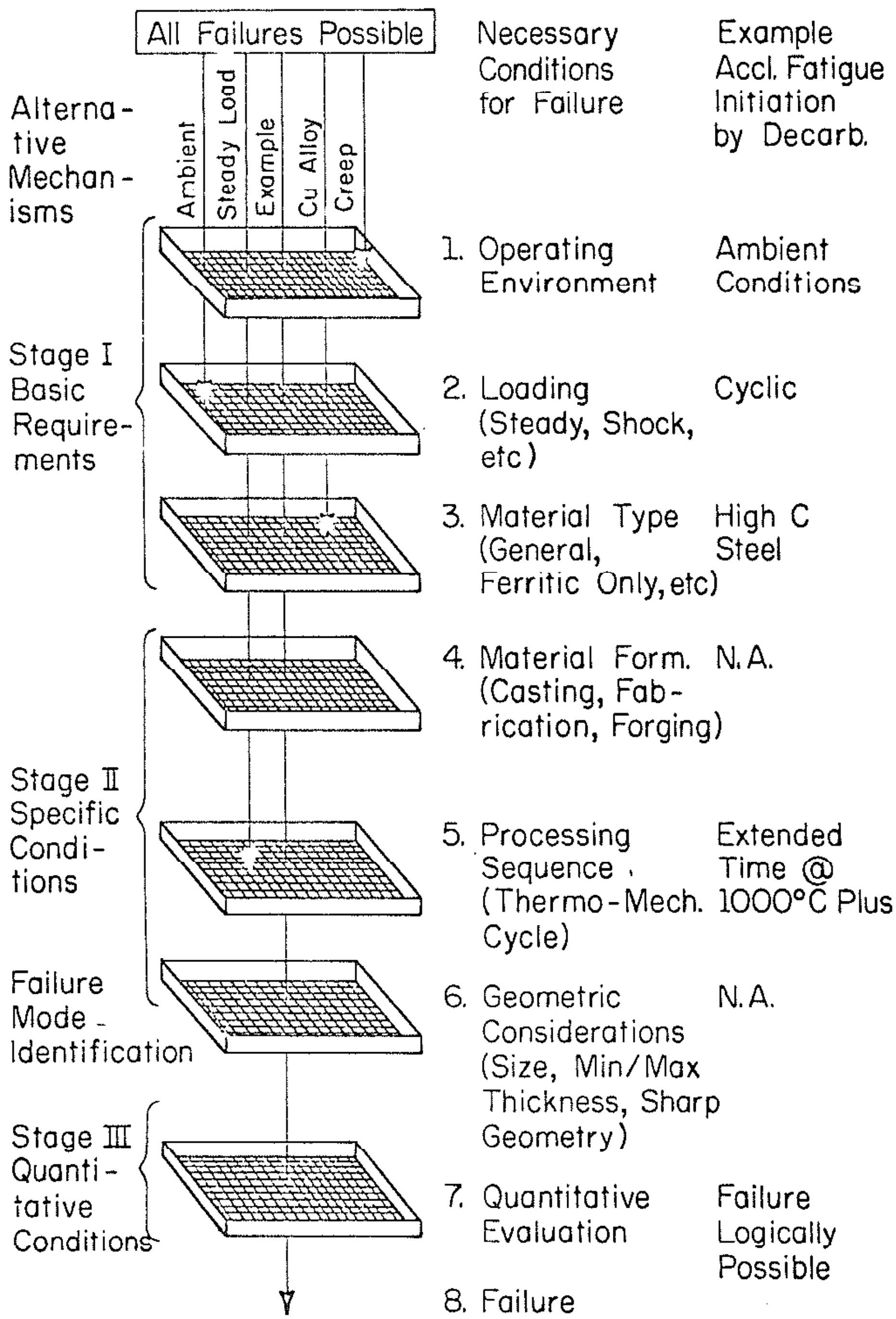


Figure 6 Illustration of Filtering Process Used.

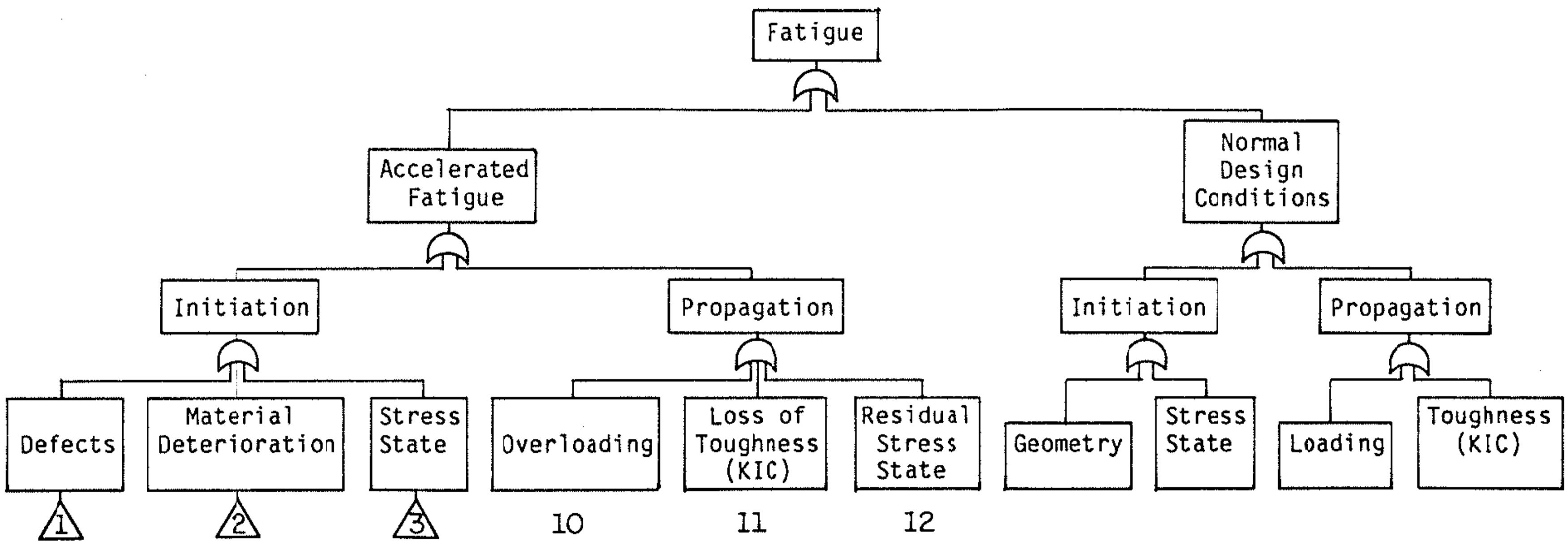


Figure 7a Fault Tree.

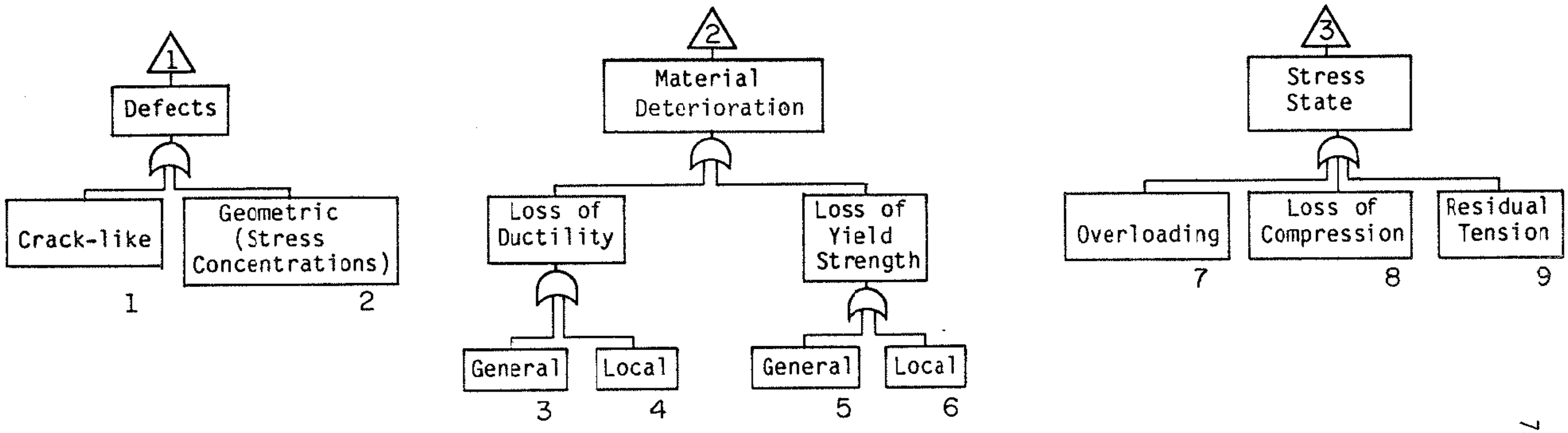


Figure 7b Fault Tree.

1. Crack-like Defects
   1. Pre-existing cracks
   2. Hot tears
   3. Burning and overheating
   4. Forging seams and laps
   5. Fretting, galling, rubbing, and scoring
   6. Quench cracking
   7. Strain-age embrittlement

2. Geometric Defects
   1. Section changes--threads, fillets, re-entrant corners, holes, etc.
   2. Weld defects--undercuts, lack of penetration, incomplete fusion, shrinkage pipe, voids
   3. Inclusions (inhomogeneous material)
   4. Coarse grains
   5. Surface fissures
   6. Corrosion pits
   7. Tool marks and rough grinding
   8. Poor fit-up

3. General Loss of Ductility
   1. Burning and overheating
   2. Improper heat treatment--time, temperature, and environment
   3. Improper nitriding
   4. H_2 embrittlement from hydrogen in environment

4. Local Loss of Ductility
   1. Banded microstructure
   2. Weld HAZ
   3. Improper weld material
   4. Martensite from localized heating
   5. Oxygen precipitation at grain boundaries

5. General Loss of Yield Strength
   1. Improper material--low hardenability
   2. Overall decarburization
   3. Overaging
   4. Improper heat treatment for hardness desired

Figure 7c Fault Tree.

6. Local Loss of Yield Strength
    1. Surface decarburization
    2. Banded microstructure (ferrite and pearlite, etc.)

7. Overloading (Initiation)
    1. Improper installation (misalignment, etc.)
    2. Improper material for loading
    3. Asperities
    4. Improper lubrication
    5. Magnitude of applied load excessive
    6. Loading not designed for

8. Loss of Compression
    1. Improper peening
    2. Subsequent heat treatment removes effect of peening

9. Residual Tension (Initiation)
    1. Plastic deformation by straightening, bending, etc.

10. Overloading (Propagation)
    1. Improper installation (misalignment, etc.)
    2. Improper material for loading
    3. Magnitude of applied load excessive
    4. Loading not designed for

11. Loss of Toughness
    1. Burning and overheating
    2. Improper material for loading

12. Residual Stress State (Propagation)
    1. Residual tension by straightening, bending, etc.

Figure 7d Fault Tree.

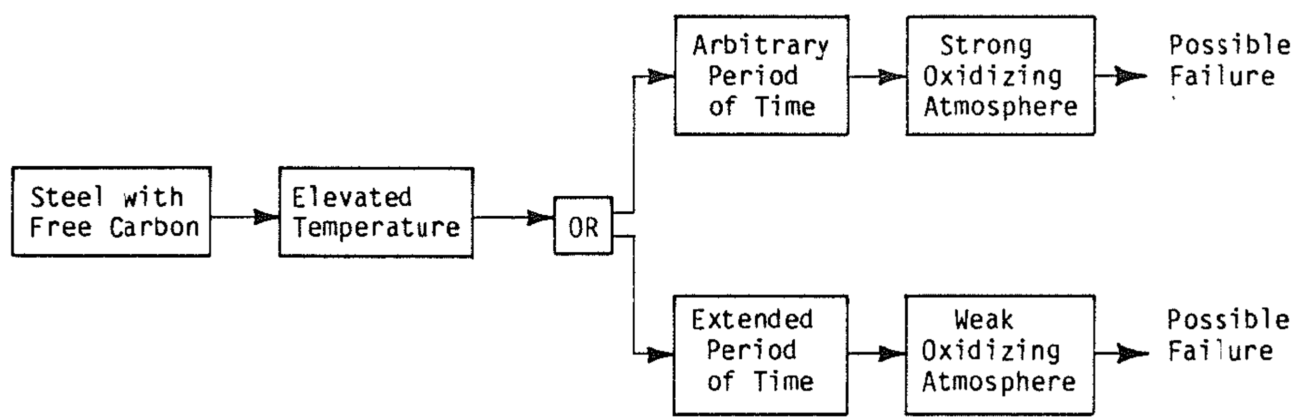


Figure 8 Decarburization Material Failure Logic Model.

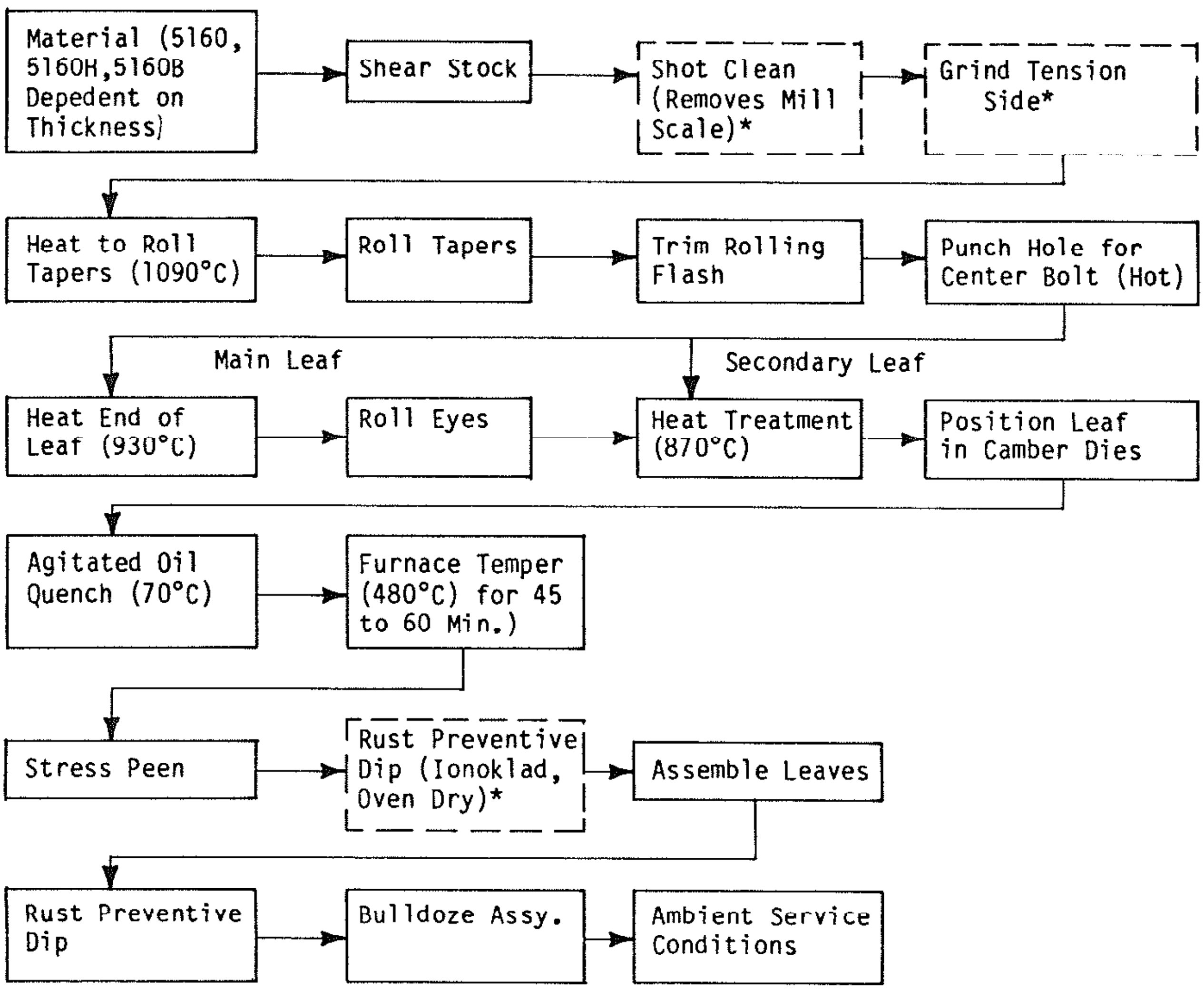


Figure 9 Truck Leaf Spring Production Flow Diagram.

*Optional

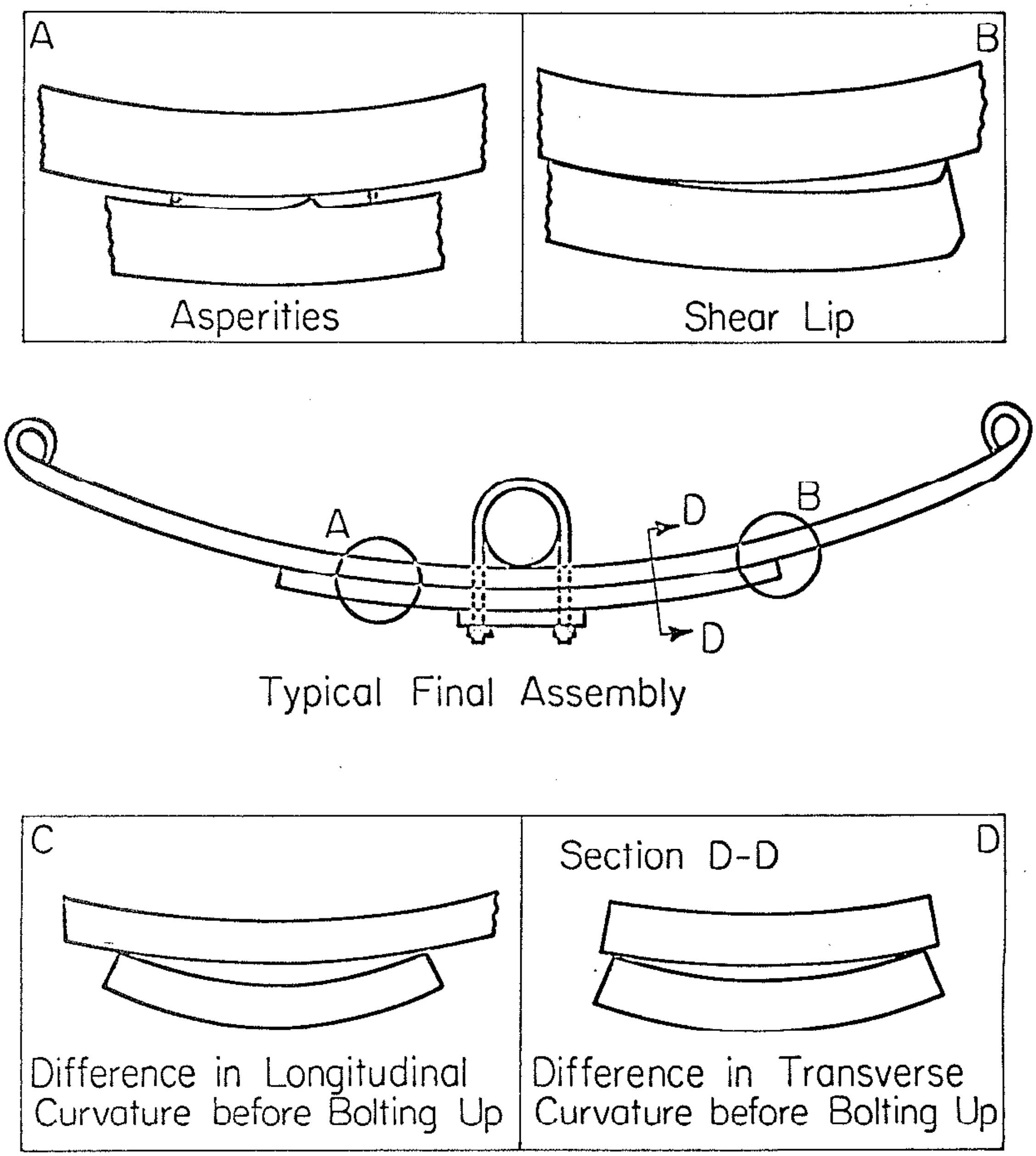


Figure 10 Fretting II Geometric Incongruencies.

Failure Possibility / Process	Decarburi-zation I	Fretting I	Initial Crack-like Defects	F.P.I. Crack-like Defects	Decarburi-zation II	Strain Age Embrittlement
Material Procurement			☐			☐
Shear Stock				☐		
Shot Clean						
Grind Tension Side				☐		
Heat to Roll Tapers	☐				☐	
Roll Tapers	☐			☐	☐	
Trim Rolling Flash	☐				☐	
Punch Hole for Center Bolt	☐				☐	
Heat End of Leaf	☐				☐	
Roll Eyes	☐			☐	☐	
Heat Treatment	☐				☐	
Position Leaf in Camber Dies	☐				☐	
Agitated Oil Quench						
Furnace Temper						
Stress Peen						☐
Rust Prevention Dip						
Assemble Leaves		☐				
Rust Preventive Dip						
Bulldoze Assembly						☐
Ambient Service Conditions		☐				☐

Note: The processing elements of Decarburization I, Decarburization II, and shear stock, roll tapers, trim rolling flash, roll eyes, and bulldoze assembly under Fretting II all have the potential of resulting in failure, either individually or cumulatively. For conciseness these elements have been listed cumulatively, as opposed to individually, under the respective failure possibility.

Figure 11a Manufacturing Processes versus Failure Mechanism Check List.

Failure Possibility / Process	Instant. Quench Cracking	Delayed Quench Cracking	Incomplete Martensite	Retained Martensite	Fretting II	Retained Ferrite	Loss of Res. Stress State
Material Procurement							
Shear Stock					☐		
Shot Clean							
Grind Tension Side							
Heat to Roll Tapers							
Roll Tapers					☐		
Trim Rolling Flash					☐		
Punch Hole for Center Bolt							
Heat End of Leaf							
Roll Eyes					☐		
Heat Treatment						☐	
Position Leaf in Camber Dies							
Agitated Oil Quench	☐	☐	☐				
Furnace Temper				☐			
Stress Peen							☐
Rust Prevention Dip							
Assemble Leaves					☐		
Rust Preventive Dip							
Bulldoze Assembly					☐		
Ambient Service Conditions					☐		

Note: The processing elements of Decarburization I, Decarburization II, and shear stock, roll tapers, trim rolling flash, roll eyes, and bulldoze assembly under Fretting II all have the potential of resulting in failure, either individually or cumulatively. For conciseness these elements have been listed cumulatively, as opposed to individually, under the respective failure possibility.

Figure 11b Manufacturing Processes versus Failure Mechanism Check List.

Failure Possibility / Process	Decarburization I	Fretting I	Initial Crack-like Defects	F.P.I. Crack-like Defects	Decarburization II	Strain Age Embrittlement
Material Procurement			O			O
Shear Stock				O		
Shot Clean						
Grind Tension Side				O		
Heat to Roll Tapers	O				O	
Roll Tapers	O			O	O	
Trim Rolling Flash	O				O	
Punch Hole for Center Bolt	O				O	
Heat End of Leaf	O				O	
Roll Eyes	O			O	O	
Heat Treatment	O				O	
Position Leaf in Camber Dies	O				O	
Agitated Oil Quench						
Furnace Temper						
Stress Peen						
Rust Prevention Dip						
Assemble Leaves						
Rust Preventive Dip						
Bulldoze Assembly						
Ambient Service Conditions						

Note: The processing elements of Decarburization I, Decarburization II, and shear stock, roll tapers, trim rolling flash, roll eyes, and bulldoze assembly under Fretting II all have the potential of resulting in failure, either individually or cumulatively. For conciseness these elements have been listed cumulatively, as opposed to individually, under the respective failure possibility.

Figure 12a Manufacturing Processes versus Failure Mechanism Revised Check List.

Failure Possibility / Process	Instant. Quench Cracking	Delayed Quench Cracking	Incomplete Martensite	Retained Martensite	Fretting II	Retained Ferrite	Loss of Res. Stress State
Material Procurement							
Shear Stock					O		
Shot Clean							
Grind Tension Side							
Heat to Roll Tapers							
Roll Tapers					O		
Trim Rolling Flash					O		
Punch Hole for Center Bolt							
Heat End of Leaf							
Roll Eyes					O		
Heat Treatment						O	
Position Leaf in Camber Dies							
Agitated Oil Quench	O	O	O				
Furnace Temper				O			
Stress Peen							O
Rust Prevention Dip							
Assemble Leaves							
Rust Preventive Dip							
Bulldoze Assembly							
Ambient Service Conditions							

Note: The processing elements of Decarburization I, Decarburization II, and shear stock, roll tapers, trim rolling flash, roll eyes, and bulldoze assembly under Fretting II all have the potential of resulting in failure, either individually or cumulatively. For conciseness these elements have been listed cumulatively, as opposed to individually, under the respective failure possibility.

Figure 12b Manufacuring Processes versus Failure Mechanism Revised Check List.

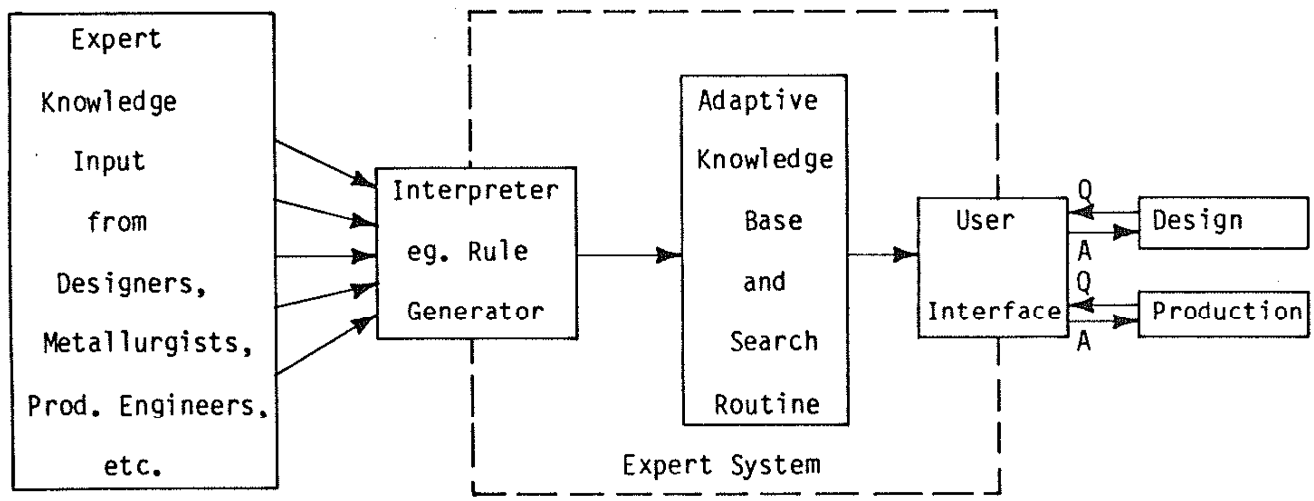


Figure 13 Diagramatic Representation of an Expert System.