TURBINE STEAM PATH
MAINTENANCE AND REPAIR

Volume One

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PennWell®

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LIST OF ACRONYMS

AA	arithmetic average
AISI	American Iron and Steel Institute
BHN	Brinell Hardness Number
CLA	centerline average
EDT	enthalpy drop test
EOH	equivalent operating hours
ESV	emergency stop valve
FEA	finite element analysis
HAZ	heat affected zone
HCF	high-cycle fatigue
LCF	low-cycle fatigue
LP	low pressure
NOH	normal operating hours
NPF	nozzle passing frequency
ppb	parts per billion
RMS	root mean square
SCC	stress corrosion cracking
SPE	solid-particle erosion
T-G	turbine generator
TTD	terminal temperature difference
UTS	ultimate tensile stress

FOREWORD

After more than 100 years of progressive invention and improvement, the steam turbine continues to reign as the prime mover of the world's power generation industry. Innovations such as Edison's light bulb and Tesla's induction motor resulted in a phenomenal demand for electric power driven by steam turbines, which have grown exponentially to more than 750,00 megawatts (1 billion HP) of capacity in the U.S. and almost 3,000 gigawatts worldwide. Steam turbines now generate more than 80% of the total electric power throughout the world.

Since the inception of modern day steam turbines by such designers as Parsons, Curtis, Rateau, and DeLaval in the late nineteenth century, Rankine cycle thermal efficiencies have improved from 5% to almost 42%. State-of-the-art combined cycle efficiencies employing steam and gas turbines now exceed 60%. Similarly, the power output of steam turbines has steadily increased from just a few kilowatts to more than 1,500 megawatts in a tandem compound shaft configuration.

Mr. William Sanders has followed in the tradition of such illustrious technical authors as Stodola (1905, 1927) and Salisbury (1950). Whereas these previous authors concentrated on the mechanical and thermodynamic aspects of steam turbine design, Mr. Sanders has focused his text on the equally important aspect of proper maintenance and repair, and their effect on turbine thermal efficiency and reliability. Mr. Sanders' text also includes areas not previously addressed, such as steam path solid-particle erosion.

Mr. Sanders' text is extremely well organized and contains many excellent illustrations, photos references, and case histories gathered from his now 40+ years of field experience and design background.

PREFACE

The Turbine Steam Path, Damage, Deterioration, and Corrective Options

This book has been prepared for those technical people responsible for the operation and maintenance of steam turbines.

Steam turbines represent a complex technology for units commonly designed to operate hundreds of thousands of hours while being subjected to a severe environment and a variety of operating phenomena capable of degrading their condition. These units are required to continually operate in a reliable, safe, and cost effective manner. Under such circumstances, these units cannot maintain their original design-specified level of performance indefinitely. All units will deteriorate with age. Owners anticipate this, and designers will normally leave an adequate margin, knowing that some level of such deterioration is tolerable.

The technology of steam turbines—while mature—continues to evolve. More accurate and time-responsive diagnostic tools and techniques are becoming available to assist in predicting when a unit has deteriorated to the extent that corrective action is required. Similarly, tools are available to assist the operator in analyzing problems and determining the effective corrective action best suited to the condition causing deterioration. The improved understanding of unit condition and rates of deterioration now achieved, together with advances in materials, should allow units to be maintained in a manner that will help minimize maintenance concerns and costs.

It is the premise of this book that units “as supplied” will fulfill two basic requirements:

- It is assumed the unit “as designed” represents an optimum selection of component sizing and arrangement
- It is assumed the unit “as delivered” meets design specification within the range of tolerances provided by the design engineer, i.e., unit components have been manufactured, assembled, tested, and installed in such a way that they are in compliance with the original design specification

The implication of this second assumption is that if nonconforming situations or conditions arose during the total manufacturing process (and exist within the unit), they have been evaluated by a competent design authority in the engineering organization of the manufacturing company and have been assessed as not having an adverse impact on the potential performance of the unit.

In terms of turbine unit components, “design optimum” is a difficult term to define. The entire design process is one of compromise by the designer who wants a unit to be both efficient and reliable. These requirements often represent competing demands, forcing the designer to select from among various elements, possibly electing to downgrade one aspect of these requirements to meet the demands of the other. This is done consciously and with detailed evaluation to provide a balanced selection.

Units delivered by a manufacturer represent the supply of elements that conform to the design principles established by his or her design function, and conform with the best technology available to that supplier at the time the design specification was prepared. However, the operator must recognize that the labor and material costs involved in building a steam turbine are high, and turbine suppliers must be able to produce units at competitive levels sufficient to allow them to achieve a profit margin enabling them to sustain business as well as finance further development.

Many power systems are currently experiencing significant changes in how they operate. Pressures from deregulation, environmental concerns and legislation, and an aging fleet of power generating equipment is shifting emphasis from the installation of new capacity to the maintenance and care of the old. There is a continuing increase in demand for electric power but new capacity installation is not keeping up with it. Operators of turbine generators are therefore required to meet this demand with their existing fleets—aging units requiring greater care to reduce the possibility of forced outages. The prospect of units experiencing extended outages as damage is found at planned outages.

Historically, as units have aged they have tended to be used less frequently. They are initially placed on spinning reserve and ultimately placed in reserve, mothballed, or retired—their capacity replaced with newer, more efficient units. An advantage of this dwindling reserve is that older units have continued to operate at high load factors and therefore become less susceptible to the rigors of start-up, shut down, and the associated thermal transients. Unfortunately, there have also been fewer opportunities for plant maintenance to proceed with the maintenance outages required to maintain unit operational health.

Maintenance problems associated with keeping aging units available are only going to increase. Operators who are expected to provide power on demand are going to experience even greater future challenges of damage and deterioration. They will be expected to identify not only the damage, but also the causative effects, and then find immediate solutions that will not jeopardize system security.

This book examines the damage deterioration and failure mechanisms occurring with unfortunate consequences—on some units, with monotonous regularity—within the turbine steam path. These various forms of degradation can be the result of a number of factors related to conditions often beyond the control of operating and maintenance personnel. However, even if the steam turbine is operated precisely as intended by design, and suffers no external degrading effects for its entire operating life, the steam environment is one that can cause components to suffer various forms of distress. Under normal circumstances, the design process selects and defines individual components suitable for the design operating life of the unit (normally about 200,000 hours). At a mean load factor of about 75%, this represents a 30-year operating life.

A number of unavoidable influences affect the operating life of the various components comprising the turbine. These include the steam environment itself, the stresses induced in the components by rotation, and stresses induced in various portions of the unit by expansion of the steam through the blade passages. There are also the effects of the high- pressure steam, causing high-pressure drops across some components that must be contained by the casings.

External factors that can affect the reliability of components of the steam path and act to lower the expected operating life include the possible formation of corrosive elements at various locations within the steam cycle, or impurities gaining access from in-leakage at sub-atmospheric pressures. There can be unit trips caused by a number of circumstances, from system trip electrical faults to lightning strikes on power lines. Many of these factors, while possibly occurring in a 30-year operating life, cannot be anticipated in terms of when, where, how many, or how severe their effects might be.

The damage and deterioration that occurs within the steam path can be of several forms. It can result in a gradual material loss—the growth of a crack—or an immediate failure causing a forced outage. Gradual deterioration can (depending upon type and location) be monitored and replacement parts made available, or corrective action taken to rectify the situation before it extends to an unacceptable degree. Immediate failure is most often the consequence of either mechanical rupture or the presence in the steam path of some foreign object, either generated within or having gained access from some external source (including "drop-ins").

In writing this book, I have tried to present information that plant personnel will be able to use to make value judgments on the type and severity of any damage, suggest possible causes, and then consider the most appropriate corrective actions that are available. To aid in the recognition and classifying of operational damage and deterioration, photographs are used to illustrate unacceptable or suspect conditions.

Many of the damaging phenomena considered in these chapters do not occur in isolation. It is possible that several can and will occur simultaneously, demonstrating that components are subjected to more than one degrading influence. A condition may initiate due to one damaging mechanism introducing a condition of weakness, which then allows another mechanism to become predominant and drive a component to failure. This situation often occurs even though the driving mechanism would not have been capable of causing failure had not the weakness been introduced by the first, or initiating mechanism.

Before considering degradation and failure in any detail, it is important to define what constitutes failure and/or deterioration. An important consideration in any case of evaluation and condition assessment of a turbine is establishing what constitutes failure. The definition I find most acceptable is this: *A condition exists within the unit that while it would not prevent the unit from returning to service and continuing to develop power, it could force it from service before the next planned outage*. Various other definitions exist, and the definition of failure used in any situation—and therefore the responsibility for correction—can be controversial. This controversy is to some extent aggravated by possibilities; *e.g.*, a crack that has been determined to exist may be predicted by the methods of fracture mechanics to be growing at a rate that would not cause complete rupture, forcing the unit from service before the next planned outage.

As reserve power margins diminish, steam turbines—that currently have operating periods between major maintenance outages of three to eight years—could be forced to operate longer than intended when they were originally returned to service. Under these circumstances, it is difficult when making a prediction of a unit's future operation, to be certain there will not be some major change in its operating parameters. Parameters that can influence an acceptable definition of failure in any situation include the exact operating period, the unit load pattern, and the steam conditions the unit will experience over a number of years.

A simple and conservative solution to this definition of failure would be to change *any* suspect component showing any crack or unacceptable damage-or-deformation indication. This may appear to be an expensive option, but is considerably less expensive than a forced outage requiring weeks or months to open, repair, await replacement parts, replace those parts, close the unit, and return it to service.

Defining efficiency deterioration is somewhat easier. It is even possible to quantify such deterioration in terms of reducing steam path efficiency and unit output. What is *not* possible to determine is the extent of any mechanical deterioration that may occur and cause efficiency deterioration. This is an unknown situation not recognized until complete mechanical rupture occurs. There is normally no manner to predict such an occurrence—damage could be in the incubation phase—even when an examination of the steam path is made at maintenance outages.

During operation, certain situations and phenomena are known to occur that have the potential to initiate damage or to cause deterioration in performance. These damaging and deteriorating phenomena can be of a continuous or intermittent nature, produced as a consequence of transient operating or steam conditions. Such phenomena can also be the result of sudden mechanical failures of components that cause more extensive consequential damage. The most commonly occurring of these degrading effects are related to the formation of moisture in the steam path or solid foreign particles, possibly from the boiler or scale generated within the superheater and reheater tubes. Other sources include chemical contaminants that are introduced, or gain access to the steam path on which they are deposited, and possibly act as corrosive elements. The other principal degrading condition is the operational phenomena occurring during the operating life of the unit.

The first two chapters of this book provide general information. The first outlines what is considered necessary to define and constitute a maintenance strategy that represents management's commitment to maintaining a healthy system. This chapter also outlines means of monitoring conditions indicative of damage. The second chapter deals with the spatial arrangement within the steam path and the factors that affect it. This is important because the performance (efficiency and reliability) of a turbine is influenced considerably by the alignment of the unit and the resulting axial and radial clearances and "laps" that are achieved in the hot operating condition.

Chapters 3, 4, 5, and 6 discuss the various phenomena known to affect both the efficiency and structural integrity of the components. In the second volume, chapters 7, 8, and 9 consider repair and refurbishment options currently available. Fortunately, there are ever-present advances in these technologies, and as experience is gained, newer and improved methods develop to be applied to older units so they can continue to operate with high levels of availability—often with improved efficiency. Chapter 10 considers seal systems and gland rings, and provides means of estimating the financial penalties associated with excessive leakage. Seals are one area where operators and maintenance personnel can influence the cost of power generation, and help reduce the cost of power to their customers.

The final two chapters, 11 and 12, relate to quality and the inspection of elements being manufactured to replace damaged components. This is an area where many engineers feel the cost of undertaking such inspections is difficult to justify. However, what happens when components—manufactured when they are required in an emergency to return a unit to service—have any form of fault and force the unit from service prematurely? In such a case, the cost of inspection—ensuring that a supplier's quality program is prepared and operating properly—is well justified. It is often said, "There isn't time and money to do it right, but there is always time and money to correct it." This statement is well applied to the manufacture or repair of components in an emergency, because the cost of a second outage is just as high as the first, and far more embarrassing.

Because the steam turbine is a thermal machine designed to convert thermal energy to rotation kinetic energy, I have included an appendix that provides the basic thermal relationships required to understand the turbine and its operation.

Situation evaluation

The more susceptible areas in any turbine unit are a function of many complex factors—individual stress levels, stress concentration, mode of operation, and the operating environment. Individual components are also greatly influenced by the expertise with which the parts were designed, manufactured, and assembled, and the operating transients to which they have been subjected. The diversity of the factors that can contribute to damage precludes any generalization of cause or value. Steam path components are subjected to high stress, both direct and alternating. Many parts operate at high temperatures and are of complex forms interacting with one another in unpredictable ways. These factors, when combined with load and temperature transients that occur during operation, combine to make the steam path highly sensitive and a major source of concern to the designer and operator.

While some concerns are common to most operators, the type of deterioration or damage to which any component or area is subjected normally varies from unit to unit. This accounts for the variety of concerns expressed by maintenance staff, and the different dispositions of the various nonconforming conditions that will be developed in any situation.

In many instances when corrective action is required, there is no optimum solution that can be followed without deviation. Operation and load demands will often negate the optimum. At other times, costs, special tools, skills, and the availability of replacement parts could require some form of compromise. These compromise solutions may have to be adopted from necessity, but the final disposition should provide the best balance between cost, risk, and the immediacy of returning the unit to service.

The logical approach to maintenance and repair dispositions is:

- Consider the available alternatives in terms of the original design requirements of the affected components
- Evaluate possible solutions in terms of departure from the design specified requirements

Many “repair” or “accept-as-is” dispositions will have only a limited effect on unit performance, and can be readily accepted. Other repairs can be proposed and accepted, representing a compromised condition. Such options should only be accepted on the basis that the unit will be operated with this compromised solution for as short a period as possible, and that the selected option does not represent a significant level of risk in the short term. If this is possible, plans should be put into effect immediately to develop an acceptable solution that can be undertaken within a reasonable time.

The maintenance options

The satisfactory performance of a steam turbine is influenced considerably by the manner and expertise with which it is maintained, and the load patterns it follows. While the plant operating engineer can control, to a large degree, the maintenance of the units for which he is responsible, he is unfortunately unable to exercise little influence on operating patterns. This is a responsibility of dispatchers who have a mandate to serve the demands of their clients rather than the turbine generators of their system.

For maintenance to be cost-effective, it must be planned. When signs of distress, excessive wear, misalignment, or component deterioration are detected, the need for corrective action must be considered. These corrective actions should help ensure the situation does not deteriorate further, to the extent the unit is placed on a forced outage status, severely load limited, or suffers an unacceptably high degree of deterioration in efficiency.

There are general maintenance requirements for any unit. Guidance for these is provided by the designer and should be followed for all routine matters. The designer will also provide recommendations for the operating time between opening sections of the unit for periodic maintenance and examination. During these maintenance outages, any findings that could affect unit performance must be reviewed in relation to their possible long-term effects.

Maintenance actions

Opening a unit for maintenance provides the opportunity to make repairs or to install replacement parts when the necessary skills and special purpose tools are available. Such an opening also allows replacement parts to be ordered, which can be placed in the unit at the current or later outage, depending upon the delivery and required period of the outage. Replacement is made when an evaluation of any found operational nonconformance is judged to be placing the unit at risk if returned to service without correction. A detailed evaluation of each nonconformance should be made and it should indicate if, and what actions are required.

The principal purpose of a steam turbine maintenance inspection is to detect potential problems at an early stage. If this is not done, relatively minor situations could progress to the extent a forced outage or excessive loss in unit output and efficiency could occur. During such a maintenance inspection outage, parts can be examined visually for indications of failure, wear, or distortion. Also, nondestructive tests can be applied to critical components to determine if their ability to continue to perform satisfactorily has deteriorated and if so, what remedial action should be taken, or planned.

A nonconformance in any part of the steam turbine unit is considered to have occurred when there are signs of mechanical failure, excessive wear, or any form of deterioration that has the potential to adversely affect the performance of the unit. Such nonconformances must be reviewed for its short- and long-term effects.

As soon as unit inspection indicates a nonconforming condition has been found, it must be evaluated. The logic process of evaluation for both availability and efficiency is considered in chapter 1. This chapter outlines avenues the maintenance engineer should explore in deciding what corrective action needs to be taken. There are four decisions that can be reached. In some circumstances the decision is relatively simple, and is in fact obvious. In other situations, a decision is made based on the probability of failure, the possible cost of repair, and ultimately, the reparation of consequential damages that are the result of not taking corrective action. These four options can be considered:

- scrap and replace
- repair
- rework
- accept-as-is

Of these decisions, possibly the most difficult and potentially most controversial is the latter—accept as is—a disposition that allows a component to return to service with no effort made to correct the nonconforming condition. There are two reasons for reaching and deciding upon this course of action:

- *There is little need to make any corrections.* To make them will add no or marginal improvement to unit performance and the condition will not place the unit at risk
- *The cost of replacing, repairing, or reworking cannot be justified.* This is often a judgment call on the part of the engineer and can only be made if he or she is aware of any risks involved

Such a decision should not be made as a desperation measure. The risks, if any, should be fully evaluated. The options and the probability of failure—from an extended outage to operation—must be fully considered.

Therefore, the evaluation process can be a complex one. Occasionally, the solution is self-evident—such as when partial failure has occurred, or when excessive damage exists. The most difficult decisions are those related to suspected damage or deterioration, and those for which it is difficult to determine the cause. In these instances of uncertainty, mature judgment is required, together with knowledge of the operating and maintenance history of the unit. This knowledge should help in the evaluation. The information in this book can also provide confidence in the selection of the final disposition.

The availability of replacement parts, special skills, and tools will often influence which decision is reached. Care must be exercised to ensure that availability or non-availability of replacement parts does not force the owner/operator into a decision ultimately causing more expense and increasing the overall risk level to an unacceptable degree.

Often, alternatives to these potential solutions are available. Some may degrade a unit's rating or impose other restrictions in terms of maximum output, or the time for which a unit can be operated. The compromise correction is ultimately more acceptable over the short-term, while the owner/operator arranges for a more palatable long-term solution.

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Chapter

1

Considerations of a Turbine Steam Path Maintenance Strategy

INTRODUCTION

Although most parts of the steam turbine are capable of suffering mechanical damage—and do sustain it—some areas or components suffer greater levels of deterioration than others. Why some areas in any unit are more susceptible than others is a function of many complex factors—individual stress levels, stress concentration, the mode of operation, operating environment, and the manner in which the unit is maintained. Other critical factors involve the operating transients to which components are subjected. This diversity of factors that can influence the potential for damage precludes any ability to state a generalization of causes or of value. Despite this fact, the area of the unit having a considerable potential to affect performance—and of raising the concern of the operating and maintenance engineer—is the steam path.

repairs and others that would allow refurbishment sufficient for the unit to be returned to service until the next outage, when replacement parts could be installed

- To remove affected parts. This can sometimes allow the unit to operate at a de-rated condition. However, even to do this often requires the installation of components such as pressure reducing plates (to correct pressure distribution throughout the unit to meet more closely the design conditions), which will allow the unit to operate without further unacceptable deterioration

The action the owner selects depends upon economic considerations of the total situation. This requires a careful evaluation of the options available under the actions items listed above. This evaluation should determine the most economical solution, consistent with returning the unit to a satisfactory mechanical condition.

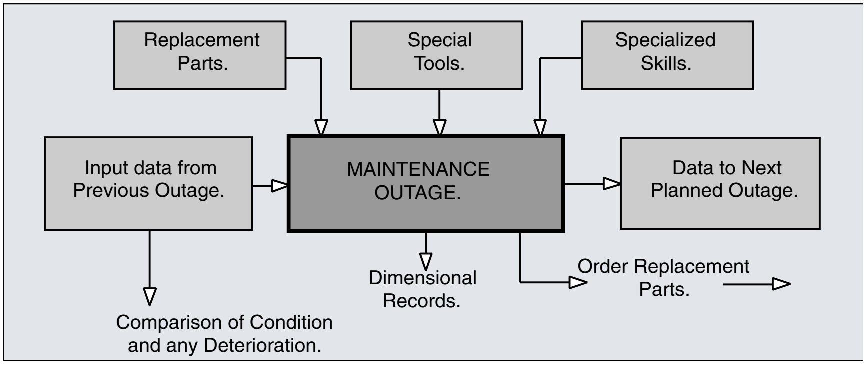

Fig. 1.2.1—The results of three openings impact on each outage, the previous in terms of the preparation for the present, the present for corrective actions identified for the future, and also to develop plans and work scopes for repair or refurbishment at the next.

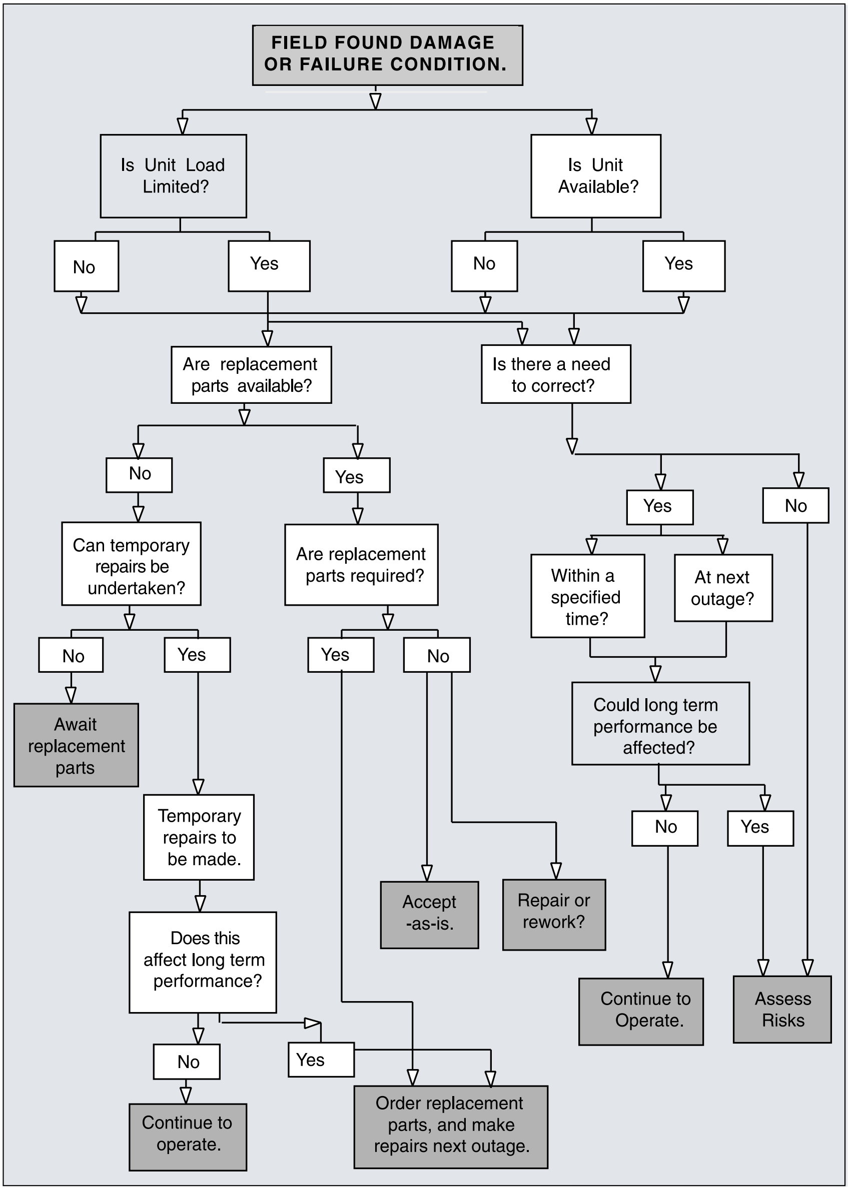

Fig. 1.8.1—The "Logic Review Process" when a nonconforming condition is found in the unit at maintenance inspection. The final decision of corrective action is dependent upon many factors including the availability and delivery of replacement parts. The maintenance engineer must evaluate the options and make a decision of the best long term solution.

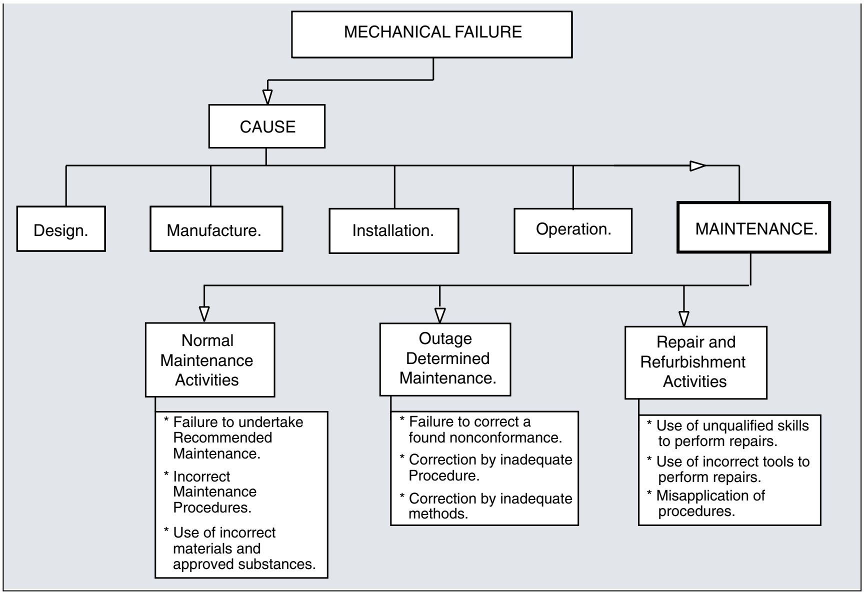

Fig. 1.9.6—The most likely influences from poor maintenance procedures which could contribute to component failure.

The examination of a failure

Considering the causes listed above, when a failure or deteriorating condition is found to exist, it is important to identify the actual cause and, to the greatest extent possible, establish if it was the result of design, manufacture, installation, operation, or maintenance. This can become a difficult and often impossible task. There are no rules or guidelines that can be applied. It often takes considerable investigation to identify both the cause and the initiating condition.

Often, if the initiating condition can be identified (*i.e.*, inferior or inadequate material, poor process control, overheating of the components, etc.), it becomes considerably easier to establish which of the five causes discussed above is the initiating condition.

Categorization

In categorizing components, it must be remembered that many units appear to have characteristics which make certain stages and components within those stages more susceptible to damage and deterioration. Therefore, categorization as given above should be considered as only a guide, and should not be interpreted to mean the "low susceptibility" elements will not suffer damage until after the 'high' and 'intermediate susceptibility' elements have been affected. Most owners will be aware of "rogue" stages and components that appear to fail with monotonous regularity in an otherwise acceptable unit.

While some elements may have a high susceptibility to failure or deterioration, it is possible that in the event of failure, these can be removed and the unit will continue to operate. Conversely, it is possible that low susceptibility elements must be replaced or refurbished when they do deteriorate, before the unit can be returned to service. The susceptibility level does not designate or indicate the ability of the component to force the unit from service for extended periods; rather, it reflects only the component's propensity to damage and/or deterioration.

Owners will often identify potential problem areas in their units at the first (warranty) inspection. At that time, the manufacturer will make a detailed examination of the unit and be able to identify to the operators any area or areas that have shown deterioration levels above the "norm" for the units. The owner should then decide to monitor these components, make a record of the existence of any damage present, and define or record the extent in some manner. The owner may also elect to carry replacement parts as inventory spares in the event they are required.

Monitoring efforts, when undertaken, should be concentrated on the most susceptible locations and components. A monitoring system