A Knowledge-Based System for Reliability-Centered Maintenance in the Chemical Industry.

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A KNOWLEDGE BASED SYSTEM FOR RELIABILITY CENTERED MAINTENANCE IN THE CHEMICAL INDUSTRY

A Dissertation

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

in

The Interdepartmental Program in
Engineering Science

by
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May 1998
To Jose and Lilia, my parents, for teaching me always to strive for the best;

to Jesus, my Lord, for leading me to the best;

and to Lucy and David, my wife and son, for being the best...
ACKNOWLEDGMENTS

I would like to express my most sincere gratitude to my chairman, Dr. Gerald M. Knapp for his constant guidance and help throughout my program of study. His invaluable assistance was deeply appreciated. I also thank Dr. Ye-Sho Chen, Dr. Lawrence Mann, Jr., Dr. Aiichiro Nakano, Dr. Ralph Pike, Jr., and Dr. Dennis Webster for their time and efforts while serving as committee members.

My special thanks to Dr. Dennis B. Webster for inviting me to be a part of the student body of the Department of Industrial and Manufacturing System Engineering, and providing me with the financial support needed for my academic aspirations here at Louisiana State University and at the University of Alabama.

I also want to express my gratitude to Mr. Marco Araya for his extensive contribution to the knowledge acquisition and validation phases of this project.

Finally, without the multiple sacrifices made by my wife, Lucia, this work would have been impossible. She has been the driving force of my life, and her love has provided me with the most precious gift of all, my son David.
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ABSTRACT

An innovative new framework for the implementation of reliability centered maintenance (RCM) in industrial settings was developed and implemented during this study. Fuzzy reasoning algorithms were designed to evaluate and assess the likelihood of equipment failure mode precipitation and aggravation. Furthermore, an alternative to the traditional RCM decision tree for prioritizing equipment failure modes was defined through the development of an approximate reasoning scheme. This priority scheme not only takes into account the relevancy of failure modes on local and product effects, but also their possibility of occurrence, as well as associated negative consequences on adjacent machinery.

The new RCM approach was implemented through an objected-oriented expert system built to perform reliability centered maintenance analysis on industrial chemical processes. The developed expert system reads the process flowsheet generated by ASPEN Plus, a chemical process simulation package, and, based on relevant machine operating data, it provides the user with the final process RCM availability structure diagram. This availability diagram consists of a listing of all critical machine failure modes likely to occur, prioritized according to their overall negative impact on the process, as well as important information on their corresponding local and system effects, and suggested controls for their detection.

Although the chemical process industry was selected as the application domain for this research, the developed RCM framework was designed to be extensible across the entire maintenance activity spectrum, regardless of the type of industry associated.
The prototype knowledge based system was constructed and delivered on an IBM compatible Personal Computer through an object oriented computer shell, LEVEL 5 Object.
CHAPTER 1
INTRODUCTION

1.1 Background

During the last decades, the need for identifying cost-effective maintenance programs for production plants and manufacturing facilities has generated a proliferation of global analysis methodologies oriented to the development of competent reliability management policies. Among these analytical methods, Reliability Centered Maintenance (RCM), which was first introduced by the civil aviation industry in the 1960's, is not only the most frequently used but also the technique that has proven to be the most effective worldwide.

The RCM methodology provides a practical and structured approach for arriving at a satisfactory maintenance strategy for each component of a given system. In choosing a strategy, the methodology takes into account safety requirements, maintenance costs, and costs of lost production (107). In essence, RCM can be defined as a technique for organizing maintenance activities to be cost-effective. Its central objective is to determine the actions required to ensure that all physical assets continue to fulfill their intended functions in their current operating environments.

RCM carries out its analysis by asking the following three questions:

1. What is the item's function?
2. How can these functions fail?
3. What are the consequences of its failure?
The maintenance program for each individual item is then developed based on the facts obtained from this query process. Usually, these programs cover three levels of maintenance actions. The first level has to do with leaving the item in service until it fails; at that moment, the item is either repaired or replaced. For the second type of maintenance, a schedule depicting the times at which each item has to be replaced or overhauled is developed to ensure that components will not enter the wear-out phase due to old age (see Figure 1.1). The last level of maintenance involves a periodic or continuous check of items to detect specific symptoms that a failure is upcoming (94, 100).

During the last years, several different frameworks have been adopted by industrial practitioners in order to accommodate the RCM's principles to their increasing equipment maintenance demands. As will be discussed in Chapter 2, the development of computer software packages which embed either mathematical optimizing algorithms or managerial rules of thumb or heuristics represent the most recent efforts in the area of reliability management modeling. However, most of these computer programs fail in providing a comprehensive tool for fully taking advantage of the benefits resulting from an effective RCM plan. From the available published literature, it is clear that the major shortcoming of newly developed maintenance software is its inability of conciliating the traditional RCM methodology with other heuristic approaches. That is, no one of the reported reliability management packages properly combines the use of optimizing algorithms such as linear and nonlinear models with non-optimizing techniques such as fuzzy or approximate reasoning methodologies and qualitative rules of thumb. Thus, the enormous economical and technical benefits of implementing such an integrating RCM
Figure 1.1 The Bathtub Curve
approach remains unknown to industrial entrepreneurs. The design of a computer program that can accomplish this objective would involve the creation of an intelligent system or expert system.

Expert systems have been defined as consulting systems that simulate the problem-solving ability of human experts through the use of expertise drawn from an information base and specific rules employed to interpret such knowledge (38).

There are several paradigms used to represent knowledge in an expert system. Knowledge can be expressed in rules, frames, networks, and logical predicates. Rules represent the most popular of all representation schemes. They are If-Then statements which generate conclusions once the validity of specific facts (premises) has been verified (6). A frame consists of a set of slots that contains a group of specifications describing an object, action, or event (38). Semantic networks represent a group of nodes linked to form object relationships. Predicate logic is a kind of formal logic which is used to make generalizations about propositions based on specific relationships (6).

Expert systems are structured in three distinct components (Figure 1.2). The knowledge base is a set of rules about the problem domain, supplied by the expert or obtained through in-depth research. The working memory carries out the tracking of what has been concluded or learned at any stage of a particular consultation. The inference engine evaluates what is true at any given time in the working memory and the knowledge base, resolving conflicts when necessary (38).

A computerized system can substantially improve the information handling methods of the RCM methodology by integrating the subsystems in charge of (a)
Figure 1.2 Expert System Components
managing the statistical parameters required for analyzing the characteristics of the
different component failure modes, (b) estimating the system/component failure modes
through the assessment of the failure mode effects (FME) and criticality analysis (CA),
and (c) determining the priority of preventive maintenance (PM) improvement plans (88).
In addition to this, the unification of Artificial Intelligence (AI) techniques with
conventional probabilistic methods and fuzzy measure approaches can incorporate
understanding of the fundamental dynamics among system components so that the RCM
analysis can provide appropriate and conclusive maintenance policies (105).

Expert systems have received the most attention of all AI techniques. They
emphasize the mathematical and statistical capabilities of the computer by using dialogue
and logic to determine viable courses of action or outcomes (110). Thus, it is possible to
enhance and improve the process of selecting and recommending reliability management
procedures by encapsulating the knowledge of human experts and proven mathematical
models with a versatile knowledge based system.

1.2 Problem Statement
A crucial element in successful operations is an effective plant maintenance function. In
a competitive world, the only means for companies to survive is through minimization of
their production costs without sacrificing the quality of their goods or services. For
example, it has been estimated that manufacturing companies in industrialized countries
such as the United Kingdom can save between 8% and 30% in operating costs through
improvement in maintenance policies (36). In the United States, the introduction of RCM
methodologies has proven very beneficial. For instance, the application of the RCM
approach to the nuclear power industry since the mid 80’s has generated long-term
benefits in reliability and safety improvements. Although the RCM benefits can not be immediately appreciated, Figure 1.3 shows how, the nuclear power industry has experienced annual maintenance man-hour and administrative savings of $108,000 per plant, and an average reduction of 24% in the number of corrective maintenance actions (26, 113).

Nevertheless, most of the reliability management programs followed by industries across the nation still present considerable deficiencies which undermine their potential benefits. For instance, nuclear plants in the U.S. spend about $2 billion per year on reliability management programs. Among these programs, only a small fraction are based on a clear understanding of the relative importance of different reliability management tasks and component failure modes (113). The need for an improved RCM approach originates from the fact that the conventional failure mode effects and criticality analysis (FMECA) method concentrates its effort only on the evaluation of the relevance of the failure effects, without giving any importance to the analysis of the failure environment (failure characteristics and detectability) whose control and study results are critical in generating assertive corrective and preventive maintenance policies. (88).

Traditional RCM analysis first encompasses the identification of critical components from a risk and economics perspective. Usually, a probabilistic safety assessment is carried out to establish the relative importance of the system’s components from a risk perspective. Moreover, appropriate risk measures are devised and used to effectively rank the different element failure modes which allow the determination of the individual component criticality. Once the selection of component criticality is
### One-time costs for RCM vs Cumulative maintenance man-hour savings

<table>
<thead>
<tr>
<th>Cost Trend in</th>
<th>Cost Trend in</th>
<th>After 1 year</th>
<th>After 2 years</th>
<th>After 3 years</th>
<th>After 4 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>1988</td>
<td>1991</td>
<td>$0</td>
<td>$50,000</td>
<td>$100,000</td>
<td>$150,000</td>
</tr>
</tbody>
</table>

*Figure 1.3 RCM Cost/Benefit per Major Power Plant (113)*
completed, applicable and efficient tasks are identified to prevent each component from developing its dominant failure causes (62). This identification of the optimal set of tasks required to cope with all of the dominant failure causes represents the major endeavor not yet adequately addressed by traditional RCM frameworks.

Computer-based decision support systems for Reliability Centered Maintenance can be thought as the most assertive way to deal with such an issue. According to Kobbacy (1992), the introduction of intelligent decision support systems (IDSS) can greatly benefit the problem of maintenance optimization if such systems are designed to accomplish the following main functional features (49):

1. access the history data from a company’s maintenance database;
2. check the quality of data;
3. recognize data patterns;
4. query the user for additional information, judgment, criterion, etc.;
5. select the most suitable model for the analysis of the data;
6. estimate model parameters;
7. select and optimize the model to provide an evaluation of the current and proposed optimal maintenance policy;
8. present the results in a flexible format, including a recommendation for the future maintenance policy and a comparison with current practice;
9. respond to user inquiries, perform ‘what if?’ modeling and provide explanations of decisions; and,
10. self-learn and enhance the knowledge base.
1.3 Objectives of the Research

The main purpose of this research was the development of a knowledge based system which could provide a new, more efficient RCM framework. The developed system was intended to be intelligent in the sense that it fulfilled some of the main functional features described in Section 1.2. Therefore, the specific objectives of the current research can be summarized as follows:

1. Identify the most commonly used equipment items within a specific process industry, and catalog their functions and significant failure modes.
2. Identify and catalog most common human failure modes.
3. Develop a rulebase for automating the conversion of system schematics (in a CAD-type software) to a functional system specification.
4. Develop a rulebase for identifying individual failure modes and system failure modes relevant to the functional system specification.
CHAPTER 2
LITERATURE REVIEW

Computer and manual search of the literature revealed the existence of dozens of journal articles related to computer systems for maintenance applications. However, the literature referring to the use of expert systems for assisting reliability management functions is very limited. The literature on the development of supporting maintenance software such as knowledge-based systems for RCM and other PM functions is reviewed here to illustrate the nature of the progress made in this field during the last decades. Literature on the techniques and methodologies to be employed in the development of the proposed system is discussed in Chapter 3.

2.1 The Need for Integrated Management to Improve Maintenance Tasks

Most of the software recently developed to support maintenance operations have come as a response to the increasing urge that industrial managers have for integrating equipment reliability and process safety management programs with preventive maintenance and probabilistic risk analysis methods to minimize the occurrence of unscheduled shutdowns. According to Ian S. Sutton (1995) from Fluor Daniel Inc., through the integration of preventive/reliability maintenance methodologies, such as RCM, and process safety management programs with probabilistic risk assessment, managers can improve their facilities' uptime. This integrated model provides a means for eliminating duplicated systems, coordinating reliability revisions, and ranking projects according to risk reduction criteria, which leads to reliability/safety programs that cost-effectively meet the organization's safety, environmental and operability goals (100).
The development of such integrated programs in large industrial organizations implies inherent difficulties in the execution of individual PM functions or subsystems that must handle massive amounts of history data and computations, and whose results must be evaluated, grouped and reconciled to produce an integrated effort. As a response to this difficulty, several distinct conventional computer software packages have been recently developed to facilitate the maintenance management processes. Table 2.1 depicts a summary of commonly used computer maintenance packages, presented at the 1993 Maintenance Information Systems Survey.

2.2 The RCM Methodology

RCM has been in practice for almost four decades; however, the available literature on RCM applications and breakthroughs show that its basic framework and implementation methodology has remained unchanged through the years, focusing most of the new developments on the design of computer software that can facilitate its introduction to distinct operational settings (26, 35, 57, 93, 95, 112).

According to the literature, the RCM approach can be considered as a process consisting of four major steps: (a) analysis and definition of the system’s functions and particularities, (b) failure mode and effects analysis (FMEA), (c) prioritization of failure modes, and (d) selection of suitable maintenance strategies for individual failure modes.

2.2.1 Systems Analysis

The main difference between RCM and other reliability management techniques is the fact that RCM recognizes that the most important aspect of the maintenance effort is the preservation of a system’s function, not the condition of the equipment (95). Therefore,
<table>
<thead>
<tr>
<th>Software Name</th>
<th>Developer</th>
<th>Functionality</th>
</tr>
</thead>
<tbody>
<tr>
<td>MANTRA</td>
<td>BMS Technology</td>
<td>A package for handling planned and unplanned work such as safety checks, quality routines, periodic maintenance, and equipment calibration. Moreover, it calculates breakdown and records history.</td>
</tr>
<tr>
<td>COMPASS</td>
<td>Bonner &amp; Moore</td>
<td>Real-time system which integrates material inventory control, maintenance planning and scheduling, equipment record history, preventive maintenance, purchasing, and manpower accounting.</td>
</tr>
<tr>
<td>PEMICS</td>
<td>CGRAM Software</td>
<td>An integrated system which caters for a company’s buildings, plant and equipment maintenance. Among others, it includes: breakdown and corrective maintenance, capacity planning and scheduling, planned preventive maintenance and condition monitoring.</td>
</tr>
<tr>
<td>EASE</td>
<td>COMAC Systems</td>
<td>A package designed to maximize equipment reliability and to minimize maintenance. It features plant availability statistics, on-line downtime monitoring, systems integration, fault analysis with full RCM functionality, real-time condition monitoring, statistical process control, and maintenance management.</td>
</tr>
</tbody>
</table>

(table con’d.)
<table>
<thead>
<tr>
<th>Software Name</th>
<th>Developer</th>
<th>Functionality</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAIN/TRACKER</td>
<td>ELKE Corporation</td>
<td>A fully integrated maintenance management, cost tracking, parts inventory and purchasing system which provides management control for equipment and facilities environments.</td>
</tr>
<tr>
<td>RCM Analyst</td>
<td>GasTops Ltd.</td>
<td>A software tool for RCM analysis and data management. It handles a wide variety of problems from the failure modes, effects, and criticality analysis of a particular machine system to the redesign of maintenance programs for an entire plant. The program uses a standard RCM logic tree to categorized failure effects, and select appropriate maintenance tasks.</td>
</tr>
<tr>
<td>MAIMMAN</td>
<td>Hatton Parkinson Sys.</td>
<td>A computerized maintenance management system which includes scheduling of inspections at irregular intervals, a warning where scheduled maintenance is planned on items which have recently been repaired, and identification of items that are incurring the most maintenance cost.</td>
</tr>
<tr>
<td>MLS</td>
<td>Largotim Business Solutions</td>
<td>An integral environment for maintenance planning, job control, stores management, asset history and cost analysis.</td>
</tr>
</tbody>
</table>

(table con’d.)
<table>
<thead>
<tr>
<th>Software Name</th>
<th>Developer</th>
<th>Functionality</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMPACT</td>
<td>Matrix Resource Ltd.</td>
<td>A software package which handles a wide variety of planned and unplanned maintenance work. It produces a complete plant history through reports and graphs on activities, cost and performance fault analysis.</td>
</tr>
<tr>
<td>MAP</td>
<td>OSPREY Computer Services</td>
<td>A system designed to assist in planning and scheduling regular and repetitive maintenance along with breakdowns. The system provides statistics on performance, failures, reliability for analysis.</td>
</tr>
<tr>
<td>MAXIMO</td>
<td>PSDI Ltd.</td>
<td>A maintenance support package that includes asset register, condition monitoring, failure analysis, inventory control, labor resource, and calendars.</td>
</tr>
</tbody>
</table>
the first task in implementing an efficient RCM program is the systematically examination of the system's components to fully understand their individual and combined functions and functional failures. According to Anthony Smith [1993], such an systematic analysis involves five essential items of information:

1. System description
2. Functional block diagram
3. IN/OUT interfaces
4. System work breakdown structure
5. Equipment history

A well-documented system description is needed to record an accurate baseline of the initial condition of the system's components in order to identify system modifications or upgrades which may require PM revisions, as well as critical design and operational factors that might influence the degradation or loss of the system's functions. The functional block diagram (see Figure 2.1), which is an illustration of the major operations that the system performs, represents a valuable tool for assisting the analyst in visualizing the system functional structure. The addition of all IN/OUT interfaces to the functional block diagram helps in observing and documenting the various elements that cross the system boundaries, which may ultimately become a part of the functions that must be preserved. The system work breakdown structure (SWBS) is a compilation of the components involved in each one of the functional subsystems shown on the functional block diagram; the SWBS, along with the equipment history (a written recollection of all component failures experienced over the past 2 or 3 years which require corrective
Figure 2.1 A Typical Functional Block Diagram (93)
maintenance) represent the primary source of information for identifying the failure modes and failure causes associated with the corresponding corrective maintenance actions (93).

2.2.2 Failure Mode and Effects Analysis (FMEA)

The failure mode and effects analysis is a systematic method for examining all modes through which a component failure can occur, as well as the potential effects of these failures on the overall system, and their relative criticality in terms of safety and impact on the normal functioning of the system (113).

In FMEA, the majority of failure modes are examined through two levels of analysis: the system-level analysis and the component-level analysis, respectively. Such analyses are carried out by system/component designers based on their expertise for evaluating the component, system, and plant consequences induced by the individual enlisted failure modes (88). The component failure modes and their effects are then drawn up into a FMEA list as shown in Figure 2.2.

The FMEA matrix associates functional failures, and not equipment functions, to the individual system components, since the reliability management actions devised by an RCM program focus on avoiding potential functional failures and not on restoring a previous equipment condition. Thus, the primary sources of information for constructing an FMEA matrix are the equipment history file on individual component failure occurrence, the expertise of engineers, technicians, and senior workers with hand-on experience with the equipment, and the design diagrams or blue prints of the original equipment manufacturer (93).
<table>
<thead>
<tr>
<th>Component</th>
<th>Mode</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Switch A1</td>
<td>1.1 Fails open</td>
<td>1.1 System fails</td>
</tr>
<tr>
<td></td>
<td>1.2 Fails closed</td>
<td>1.2 None</td>
</tr>
<tr>
<td>2. Switch A2</td>
<td>2.1 Fails open</td>
<td>2.1 System fails</td>
</tr>
<tr>
<td></td>
<td>2.2 Fails closed</td>
<td>2.2 None</td>
</tr>
<tr>
<td>3. Light Bulb C</td>
<td>3.1 Open filament</td>
<td>3.1 System fails</td>
</tr>
<tr>
<td></td>
<td>3.2 Shorted base</td>
<td>3.2 System fails: possible fire hazard</td>
</tr>
<tr>
<td>4. Battery B</td>
<td>4.1 Low charge</td>
<td>4.1 System degraded</td>
</tr>
<tr>
<td></td>
<td>4.2 No charge</td>
<td>4.2 System fails</td>
</tr>
<tr>
<td></td>
<td>4.3 Over-voltage charge</td>
<td>4.3 System fails by secondary damage to Light Bulb C</td>
</tr>
</tbody>
</table>

Figure 2.2 A Simple FMEA
2.2.3 Prioritization of Failure Modes

"Not all failure modes are created equal." One of the most fundamental differences between RCM and other reliability management methodologies is the understanding of such a powerful statement. Organizations are limited in their resources, and thus, emphasis must be devoted to each failure mode according to the potential impact of its respective functional failures on the overall system's performance.

The RCM process categorizes every failure mode into bins through the use of a decision structure (93, 95). Logic tree analysis (LTA) is the name given in RCM to the process of assessing the individual criticality rankings of failure modes. The basic LTA uses simple yes-no questions which lead to the classification of detected failure modes into the following labeling bins: (a) hidden failures, (b) failure with safety-associated consequences, (c) failures with minor to insignificant economical consequences, and (d) failures with significant economical results. It should be noted that the traditional LTA comprises only qualitative questions which do not involve any kind of statistical nor mathematical evaluation (88, 93). This LTA query scheme has remained basically the same from the time when the RCM methodology was introduced by United Airlines; and as it will be discussed later, it might represent one of the areas with most potential for improvement through the implementation of artificial intelligence techniques.

2.2.4 Selection of Maintenance Strategies for Individual Components

The final step in the RCM methodology is the devising of suitable maintenance strategies or tasks for each of the examined failure modes. The selected maintenance tasks must be both applicable and effective. By applicable it is meant that the tasks will prevent or mitigate a recognized failure, detect an eminent one, or discover hidden equipment
deterioration factors. By effective it is meant that the chosen tasks are the most cost-effective alternatives among the competing candidates (93).

Thus, the preventive maintenance tasks implied by the conventional RCM approach can be classified into the following four major categories:

1. Tasks oriented to the prevention of a potential failure.
2. Tasks aimed at detecting an eminent failure.
3. Tasks designed to protect a system's normal functioning from hidden failure.
4. Tasks directed to the deliberate run to failure of a component due to economic reasons.

2.3 The Quantitative Approach to Reliability Management

One of the most important objectives of an industrial reliability management program is the development of maintenance policies or strategies that can lead to optimal decisions regarding the following questions:

1. Where and when component replacement must take place.
2. Where and when inspection tasks are appropriate.
3. Where and when overhaul and repair actions are cost effective.

Mathematical models in the areas of operation research, statistical reliability, and systems engineering have been developed as a response to the need for a rapid and assertive evaluation of alternative maintenance decisions. The main purpose of such models is to effectively assess the economic consequences of selecting one strategy over the others, and by doing so, determine the most optimal decision (39). Furthermore, mathematical models can maximize equipment availability through mathematical
prediction of component failures. That is, a model can minimize equipment downtime by determining when to repair or replace an item based on the Mean Time Between Failures (MTBF) of crucial equipment components. Such mathematical computations have their basis on the reliability theory (60).

2.3.1 The Notion of Reliability

Reliability can be defined as the probability that a particular system or component will operate normally, according to certain working specifications, throughout a determined period of time (20). During the life cycle of a component (the item's repair-to-fail process), its time to failure cannot be exactly predicted since it represents a random variable characterized by the stochastic properties of the population of potential failure times. Since the item's failure time is a stochastic process, the probability of a failure occurring before some specified time \( t_i \) is defined by:

\[
\int_{0}^{t_i} f(t) dt
\]

(2.1)

where \( f(t) \) is the component's failure probability density function. Such an integral is denoted by \( F(t) \) which represents the cumulative failure distribution function. It should be clear that \( F(t) \) tends to one when \( t \) tends to infinity, which indicates that no item can survive failure during an infinite interval of time (33).

The reliability (or survival function) is the complementary function of the cumulative failure distribution \( F(t) \). Denoted by \( R(t) \), the reliability function represents the probability that a component will survive at least to a determined time \( t \), and is defined as:

\[
R(t) = 1 - F(t)
\]
Another concept originated from the reliability and failure distributions of a particular items is its failure or hazard rate, denoted by \( h(t) \). The failure rate is defined as the probability that a specific component will malfunction in the next interval of time given that it has survived, without a failure, to time \( t \). Mathematically, \( h(t) \) is determined by (33):

\[
h(t) = \frac{f(t)}{1 - F(t)} = \frac{f(t)}{R(t)}
\]

The importance of knowing an item’s failure distribution, and so its reliability and hazard rate functions, originates from the fact that decisions such as when to perform preventive maintenance on a specific piece of equipment require information about the time when its components will reach a breakdown state. Knowing the probability that a failed state might occur at any specific time results essential in determining the cost-effectiveness of alternative maintenance policies.

The failure distribution of equipment is generally obtained through curve fitting, statistical analysis, and other numerical procedures performed on failure times observations available from historical records. However, some probability distributions such as the Weibull, negative exponential, normal and log normal distributions seem to efficiently describe the failure frequency patterns presented by most industrial equipment (20, 39, 60).
2.3.2 Replacement and Overhaul/Repair Decisions Modeling

Replacement actions involve the substitution of working equipment before it reaches a failed state at which its functioning is no longer remunerative. Since the failure time of equipment is characterized by a stochastic process, the timing of a replacement action is also probabilistic.

When determining the time to perform a replacement, the minimization of the total cost (replacement and operating costs) associated with the equipment's operation is usually intended. However, according to Jardine [1973], reliability management actions should be given consideration only if the following two conditions are met:

1. The total cost of the replacement increases after the failure event.
2. The equipment presents an increasing failure rate.

The second condition is especially important. If a piece of equipment presents a constant failure rate, replacement before failure will not affect its likelihood of failing again in the next instant; thus, its preventive replacement becomes prejudicial in economic terms.

In general, the model formulation tries to determine the optimal interval of time between equipment or component replacements so that its total operation and replacement cost per unit time $C(t_r)$ is minimized, that is:

$$C(t_r) = \frac{\text{Total cost in interval } (0,t_r)}{\text{Length of interval}}$$

(2.4)

The complexity of the mathematical model varies according to the assumptions considered in the analysis. For instance, if it is assumed that the equipment can be
replaced with an identical unit indefinitely, and inflation discounting is ignored, the corresponding mathematical model that results is simple. Conversely, factors such as repairs not returning back the equipment to its “as-new state”, potential technological improvements, equipment breakdown during replacement intervals, and inflation considerations can greatly increase the mathematical complexity of the subsequent model. In that case, the model’s final result may not be a deterministic interval but rather one with a stochastic nature (48).

2.3.3 Inspection Decisions Modeling

Equipment inspection is an essential part of any comprehensive reliability management program, including RCM. Among other purposes, equipment inspection aims at (60):

1. Evaluating components in terms of potential problems.
2. Estimating the occurrence of a breakdown.
3. Scheduling repair actions to prevent a major failure.
4. Identifying key components that may precipitate a system’s failure.

Inspection can be thought as the middle point between preventive and corrective maintenance. It applies to both deteriorating systems and hidden failures. Through the mathematical formulation of inspection decisions, it is intended to determine an inspection strategy that will produce the optimal balance between the cost of periodically inspecting the equipment, and the potential loss production cost due to complete machinery breakdown (48). Thus, the main goal of the formulation is the minimization of the total cost \(C(t_j)\) involved in inspecting the equipment until either a failure is detected or the equipment reaches the failed state. \(C(t_j)\) is then defined by the following expression:
\[ C(t_i) = \frac{\text{Total expected cost per inspection cycle}}{\text{Inspection cycle length}} \]  

(2.5)

The total expected cost per inspection cycle is actually the sum of both the cost of performing the inspection \( C_{ir} \) and the cost of a system failure per unit time \( C_f \). It should be noted that the model deals with an expected cost since the time at which a failure precipitates cannot be deterministically calculated; thus, \( C_f \) can only be estimated according to the failure function \( f(t) \) characteristic of the specific piece of equipment. As in the replacement decision process, the inspection modeling effort depends on the variables considered in the analysis. It can vary from very simplistic models based on perfect corrective actions and constant inspection costs assumptions to more complex ones where, for instance, the likelihood of a safety event (an event that requires a safety system) is taken into account for the final decision (36, 48).

2.4 Approximate Reasoning in Reliability Management

Reliability analysis, equipment condition monitoring, and maintenance task scheduling are fundamental parts of a reliability management program. Traditional analytical techniques developed to address issues such as mathematical and statistical models require the knowledge of precise numerical probabilities and component functional dependencies, information which is rarely available to industrial practitioners in real life. The field of approximate reasoning can provide some guidelines for coping with such a difficulty (105). Among inexact reasoning methodologies, fuzzy set theory is one of the most widely used in describing the behavior of systems with inherent uncertainty.
2.4.1 Fuzzy Set Theory

A fuzzy set differs from a traditional or crisp set in the sense that it does not have well-defined boundaries. In a conventional set $A$, the degree of membership 1 is assigned to those objects that fully belong to the group, while 0 is assigned to objects that are not part of the set. For instance, if $A$ represents the set of integer numbers which are even, the number 24 should then receive a membership value equal to 1, while 25 should have a membership of 0 since clearly it does not belong to $A$. However, when dealing with fuzzy sets, the assignment of membership values is not so trivial.

The fuzzy set theory is concerned with those subsets in which, due to their inherent uncertainty, the transition between full membership and no membership for objects in the universe is gradual rather than abrupt (40). As an example, if $A$ is now defined as the set of large integer numbers, intuitively, the number 1 should have a membership value of 0 while number $10^{99}$ a value of 1; but what about 20, or 70, or 110? Evidently, they should receive membership values between 0 and 1. Fuzzy set theory deals with the development of special functions required for determining the degree of membership for objects belonging to fuzzy sets (46, 117).

The most commonly employed notation in the literature to denote the membership function of a fuzzy set $A$ is $\mu_A$ (44); that is:

$$\mu_A: X \rightarrow [0, 1]$$

thus, for the previous example, the numbers 20, 70, and 110 could be thought as belonging to the fuzzy set $A$ (the set of large integer numbers) with membership degrees of $\mu_A = 0.2$, $\mu_A = 0.4$, and $\mu_A = 0.6$ respectively.
In fuzzy set theory, there are three standard fuzzy set operations which are of special importance. The standard complement, \( \sim A \), of a fuzzy set \( A \) with respect to the universe \( X \) is defined for all \( x \in X \) as:

\[
\mu_{\sim A}(x) = 1 - \mu_A(x)
\]  

(2.7)

moreover, given two fuzzy sets, \( A \) and \( B \), their standard intersection, \( \mu_{A \cap B} \), and standard union, \( \mu_{A \cup B} \), are defined for all \( x \in X \) as:

\[
\mu_{A \cap B}(x) = \min[\mu_A(x), \mu_B(x)]
\]  

(2.8)

\[
\mu_{A \cup B}(x) = \max[\mu_A(x), \mu_B(x)]
\]  

(2.9)

where \( \min \) and \( \max \) denote the minimum and maximum operators, respectively (46).

For instance, if \( A \) and \( B \) are defined as (44):

\[
A = [ .7 \ 0.4 \ 0.5 \ 0.2 \ 1 ]
\]

and

\[
B = [ .3 \ 0.1 \ 0.4 \ 0.9 \ 0 \ 1 ]
\]

then:

\[
A \cap B = [ .3 \ 0.4 \ 0.5 \ 0 \ 1 ]
\]

\[
A \cup B = [ .7 \ 0.1 \ 0.4 \ 0.9 \ 0 \ 1 ]
\]

\[
\sim A = [ .3 \ 0.6 \ 0.1 \ 0.5 \ 0.8 \ 0 ]
\]

2.4.2 Fuzzy Expert Systems

An expert system is a computer-based program which imitates the human reasoning process of an expert while solving a particular problem. A fundamental component of an expert system is the inference engine, which is in charge of firing the rules contained in
the knowledge base. In a fuzzy expert system, the inference engine makes fuzzy inferences from a set of production rules which consist of fuzzy predicates and fuzzy prepositions (40, 46).

According to Zadeh [1983], an expert system must be capable of coping with three potential sources of uncertainty: the fuzziness of premises and/or conclusions of certain domain rules, the partial match between the premise of a rule and a fact supplied by the user during a consultation, and the presence of fuzzy quantifiers in the premise and/or conclusion of a rule. The use of fuzzy logic as a framework for dealing with uncertainty in knowledge based systems has proven more effective and correct than conventional techniques such as Bayesian inferencing and confidence factor analysis (40, 116).

In classical two-valued and multi-valued logics, a proposition, \( p \), is either true or false, or it may have an intermediate truth value from a finite or infinite truth-value set \( T \). Conversely, in fuzzy logic, a proposition is allowed to have a truth value ranging over the fuzzy subsets of \( T \). Thus, a fuzzy implication, \( Y \), is a function of the form:

\[
Y: [0,1] \times [0,1] \rightarrow [0,1]
\]  

which defines the truth value, \( Y(a, b) \), of the conditional implication "if \( p \), then \( q \)" given that \( a \) and \( b \) are any possible truth values of the fuzzy propositions \( p, q \), respectively.

Clearly, this function is an extension from the restricted domain \{0, 1\} of the classical implication \( p \rightarrow q \) to the full domain \([0, 1]\) of truth values in fuzzy logic.

Since the knowledge base of a fuzzy expert system consists of a collection of fuzzy propositions representing the facts, and fuzzy conditional implications constituting

29
the rules, multiple fuzzy implications are needed to assess the truth values of the encoded heuristics. Such fuzzy implications are normally inserted into a decision table which becomes part of the rule-based system. This fuzzy decision table provides a framework for systematically representing and inferring information from an uncertain environment when the expertise at hand involves imprecise rather than precise knowledge. It should be noted that, although the mathematical formulation of a fuzzy implication should uniquely and strictly depend on the nature of the expertise encoded in the corresponding knowledge based system, it must be based upon well-founded and sound fuzzy set operators. Dozens of different fuzzy logic algorithms have been developed for several distinct applications throughout the years, and a vast number of them can be found in the reported literature (40, 46, 116).

2.4.3 The Fuzzy Approach to Equipment Reliability and Maintainability

Although only a small number of scholars has seriously addressed the issue of how to handle uncertainty in the area of equipment reliability and maintainability, the importance of developing industrial reliability management programs that can cope with imprecise equipment maintenance data can not be dismissed.

Fuzzy sets can be employed for representing equipment condition and remaining life, predicting machine failures, performing component and risk assessment analysis, as well as determining the frequency and timing of reliability management actions (79, 58, 84, 91, 92, 99, 105). Particularly related to this study are the efforts of representing machine condition and system criticality through fuzzy sets. Equipment condition has been modeled using triangular fuzzy numbers (99). If \( x \) is the fuzzy variable for the condition of a particular machine (ie, \( x \) may vary from 0 to 10, being 0 a completely
failed state while 10 a perfectly functioning state), then, the functional condition of machine $B$ can be represented by the triangular fuzzy set:

$$
\mu_B(x) = \text{tri} (\alpha, x, \beta)
$$

(2.11)

which has equal spread on both sides, i.e., $x-\alpha = \beta-x$.

Moreover, Tomsovic and Baer [1996] have proposed the use of Zadeh’s fuzzy set operations for modeling component dependencies. In RCM, for instance, it is necessary to evaluate all the functional interrelationships among the system’s elements in order to assess the overall effects of the distinct component failure modes. However, for large systems, the nature of the dependencies may be unknown. Thus, fuzzy set operators, such as conjunction and disjunction operators, may denote a natural and simple way of representing the possibility of interdependencies among machines or pieces of equipment. It should be noted that these fuzzy operators need to be carefully chosen or devised so that the equipment interdependencies under scrutiny can be properly reflected in the analysis.

Fuzzy logic has also been considered for manipulating the linguistic terms that an analyst employs in performing a Failure Modes, Effects and Criticality Analysis (FMECA) (79). Linguistic variables can be adopted to describe the severity, frequency of occurrence, and detectability of failure modes. Each one of such linguistic terms can be represented by fuzzy trapezoidal numbers, as shown in Figures 2.3, 2.4, and 2.5. The degree of risk associated to each failure mode can then be determined by a devised arithmetical scheme involving the membership values deduced from the corresponding trapezoidal numbers according to the analyst’s appreciation. Finally, through a
defuzzification method or procedure, a conclusive linguistic variable (i.e., moderate, important, very important, etc.) can be resolved to determine the risk of each component failure mode.

2.5 Intelligent Computer Systems and RCM

The selected software tools listed in Table 2.1 are considered maintenance management systems in the sense that they provide an integrated environment for monitoring, controlling, and coordinating maintenance operations with all other functional activities of an organization such as process scheduling, purchasing, storing, and others. Although the importance of such systems in promoting an efficient and orderly execution of functions can not be ignored, they fail in delivering the appropriate technical and analytical means for an effective RCM implementation.

RCM bases its efforts on the monitoring of individual pieces of equipment. The most challenging aspects of its implementation is obtaining sufficient data on equipment performance such as correlated errors, faults, breakdowns, and others measures of degradation. The evaluation, grouping and comparison of such a massive amount of data cannot be efficiently handled by a general information system in which global integrating parameters are normally given greater importance. Furthermore, in RCM, for different types of components and machines, different types of maintenance policies are generated which involves a variety of failures patterns. The analysis of such patterns demands knowledge and training in using mathematical models not offered in a conventional software. Finally, the maintenance engineer is highly challenged by the nature of the information manipulated by an RCM. Certain specific operability details such as the replacement of components with different specifications or maintenance policies impose
special flexibility and versatility in the maintenance routines which makes difficult the enhancement and evaluation of reliability management tasks by conventional integrated computer systems (50, 57).

Nevertheless, knowledge based systems have been identified as a strong candidate for handling systems such as RCM. According to several scholars in the field, an intelligent decision support system composed by subsystems such as expert systems and embedded neural networks represents the best alternative to improve the performance of an RCM program. They claim that an intelligent supporting program can provide the tool to integrate all RCM data and prevent decision makers from being overwhelmed by the complexity of reliability management modeling and planning (47, 49, 50, 57, 88, 110). Moreover, since an expert system matches human heuristic thought processes, the expert systems methodology seems to be more acceptable to a maintenance engineer than the solution of a computational algorithm or other analytical procedure (82).

2.6 Expert Systems Applications in Reliability Management

This section discusses the most relevant knowledge based systems developed during the last decade for reliability management applications. Although these efforts did not yield a system that could efficiently cover all the RCM features nor reconcile the mathematical modeling with the heuristics aspect of reliability management, they do represent breakthroughs in the conventional way of managing maintenance operations and confirm the suitability of expert systems in supporting RCM functions.
Figure 2.3 Failure Mode Occurrence Ranked As Low (79)

Figure 2.4 Severity of Failure Ranked As High (79)
Figure 2.5 Failure Detectability Ranked Somewhat Moderate And Somewhat Low (79)
2.6.1 Automated Cable Expertise (ACE) (67)

One of the first reported efforts in creating an expert system for corrective and, in a sense, some preventive maintenance tasks is the Automated Cable Expertise system, known as ACE. It was developed by the AT&T Bell Laboratories in 1985 to analyze thousands of customer trouble reports for signs of potential outside-plant problems. ACE was programmed using Franz Lisp and OPS4, and delivered on an AT&T 3B2/300 computer.

The systems uses two databases: CRAS, the Cable Repair Administrator System; and TREAT, the Trouble Repair Evaluation and Administration Tool, whose analysis guides local telephone companies’ preventive maintenance programs. The final output of the system is a comprehensive report describing the place and nature of outside-plant repairs that could improve the service to the customers and save the company money.

However, ACE was designed with the purpose of assisting in cable analysis only. Its main objective is to identify the location where loop-cable analysis is needed. Thus, ACE does not carry out any real important mathematical, or probabilistic risk analysis. It makes its recommendations based on the encapsulated expertise of well-trained human analyzers. Although ACE’s recommendations involves certain reliability management strategies for improving the local cable configuration, they can be seen instead as mere corrective actions, generated through coded human expertise without a serious component failure mode analysis.

2.6.2 The SRI Program (88)

A Systematic Reliability Improvement (SRI) program was developed by the Toshiba Corporation and the Tokyo Electric Power Company to support the decision-making process of reliability management planning in nuclear power plants. The system is based
on the Reliability Centered Maintenance methodology, and integrates the following three subsystems:

1. The equipment part maintenance information control system (EMICS), which is in charge of the evaluation of component reliability and aging parameters. The maintenance management subsystem provides statistical analysis on component failure modes.

2. The failure mode effects/criticality analysis database system (FMECA-DBS), designed to classify the failure mode characteristics and their environment. The FMECA database subsystem manages data on the system/component failure modes, previously estimated by experts at the design stage.

3. The PM planning subsystem which determines the priority of PM improvement plans. It evaluates the priority or criticality of PM actions such as improved maintenance, design, quality, and operation for components and their parts through an interactive logic tree analysis.

This last subsystem represents an intelligent knowledge based system designed to provide improved maintenance guidance on PM intervals, tasks, and inspection techniques based on the analyses yielded by the other two subsystems. However, the system does not generate reliability management strategies based on inherent PM expertise or mathematical models. It just upgrades the information-handling process of traditional RCM relevant to the FMECA and logic tree analyses in order to compute the priority for reliability improvements. The system can not make a decision by itself; it needs the user to carry out the FME/CA ranking assessment, as well as to interpret the final priorities given to the different PM policies. The literature is not clear about this.
point, it seems that the user follows the branches depicted in a displayed logic tree to distinguish the most appropriate reliability improvement. Moreover, although the proposed SRI program handles some vague terms (i.e. "critical", "highly critical", etc.) to perform the evaluation of the failure modes and prioritization of PM strategies, the authors do not incorporate any fuzzy or approximate reasoning scheme to any of the system’s modules, which may evidence a major incapability of the system in handling such ambiguous variables.

2.6.3 An Expert System for FMECA (110)

Jonathan Webber from Dowty Fuel Systems has proposed and developed an expert system to assist in failure modes, effects and criticality analysis (FMECA). Although FMECA is just a part of the whole structure of the RCM methodology, it is worthwhile to discuss such an expert system here since it represents a valuable effort in proving the effectiveness of artificial intelligence in PM functions.

According to Webber, FMECA’s primary contribution is the early identification of potential failures so that they can be eliminated early in the design stage. However, the traditional FMECA activity is unable to influence design since the time that it takes to carry it out often exceeds the development phase. The FMECA methodology consists of three major steps: the system interpretation, the failure analysis, and the numerical analysis. Webber proposes that by automating the failure analysis through a knowledge based system, the FMECA duration time is then reduced, which greatly improves its effectiveness. To prove his point, he constructed an expert system for failure analysis on a hydraulic actuation system. The developed expert system models the behavior of the hydraulic fluid as it goes, under some specified conditions, through the diverse
components of the actuator. Through the elicitation of relevant heuristics on the distinct functions and failure modes of each one of the components, and the hydraulic line between them, the expert software can know which components suffered from the effect of an upstream failed component. The software then indicates if a normal liquid flow between components was detected during the simulation, and provides the FMECA for all the components of the actuator.

The results of this effort showed that the expert system carried out the failure analysis in less than a quarter of the time previously taken by the human analyst. In addition, the quality of the knowledge based failure analysis was superior over its human counterpart when used with systems incorporating ten or more components.

2.6.4 IMOS (49)

IMOS, a prototype intelligent maintenance optimization system was developed to assist in the evaluation and enhancement of maintenance routines. This system shows a very interesting configuration where an optimization module for PM routines is combined with a model-selection knowledge base. The main objective of the optimization module is to determine the interval of time at which preventive maintenance is to be performed, based on one of the following optimizing criteria: maximization of equipment availability, minimization of maintenance cost, minimization of maintenance costs while meeting availability requirements, or maximization of profit. Conversely, the model-selection knowledge base consists of nine rules (see Figure 2.6) constructed to identify the most appropriate mathematical model to be applied according to the characteristics presented by the particular situation. There are five basic models coded in the system: the deterministic model, the stochastic model, the geometric model I, the geometric model II,
and the Weibull analysis model. IMOS represents an innovative PM framework in the sense that it attempts to reconcile maintenance-routine optimization models with PM heuristics drawn on the expertise of experienced maintenance engineers. However, the simplicity of the system reduces its effectiveness. A formal failure mode effects and criticality analysis is absent from the prototype system. IMOS concentrates its efforts in determining only the most appropriate PM interval for isolated machines or components without evaluating the environment surrounding the failures; and even the computation of such an interval is based on very simplistic criteria. Furthermore, the system was not designed to consider components with variant or complex reliability functions, which causes it lack of the flexibility and versatility required for RCM applications.

2.7 Literature Search Summary

The results of the literature search clearly show the increasing interest in the utilization of intelligent knowledge based systems for reliability management operations. Such systems can considerably improve the scope of reliability centered maintenance applications.

Nevertheless, most of the reported systems fail in providing a comprehensive RCM framework that can take full advantage of both exact optimization models, and PM expertise recollected in the form of rules. Systems such as the SRI program and IMOS represent a significant step to the development of the ultimate RCM software. However, there are techniques such as fuzzy induction, and approximate or inexact reasoning that can positively contribute to the field of reliability management but have not yet been seriously considered by most researchers.
<table>
<thead>
<tr>
<th>RULE 1</th>
<th>RULE 2</th>
</tr>
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<tbody>
<tr>
<td>If Number of PM events is large and No failure events and PM cycle length is not very variable Then Apply Geometric Model I</td>
<td></td>
</tr>
<tr>
<td>If Number of PM events is large and No failure events and PM cycle is not very variable Then Apply Geometric Model II</td>
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<tr>
<th>RULE 3</th>
<th>RULE 4</th>
</tr>
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<tbody>
<tr>
<td>If Number of PM events is large and There are sufficient failure events and PM cycle length is very variable Then Apply Deterministic Model I</td>
<td></td>
</tr>
<tr>
<td>If Number of PM events is very small and Number of failure events is enough and Weib. β parameter is of CO dist. &gt; 1 Then Apply Weibull Model</td>
<td></td>
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</tbody>
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<thead>
<tr>
<th>RULE 5</th>
<th>RULE 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>If Number of PM events is very small and Number of failure events is sufficient and Weib. β parameter of CO dist. not &gt; 1 Then Stop any PM policy, report beta value</td>
<td></td>
</tr>
<tr>
<td>If Number of PM events is large and Number of failure events is large and Weibull β parameter of PM dist. = 1 and Weibull β parameter of CO dist. = 1 Then Apply Stochastic Model</td>
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<tr>
<th>RULE 7</th>
<th>RULE 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>If Number of PM events is large and There are failure events and Weib. β parameter of PM dist. not = 1 or Weib. β parameter of CO dist. Not = 1 and PM cycle length is sufficiently variable Then Apply Deterministic Model</td>
<td></td>
</tr>
<tr>
<td>If Number of PM events is large and Number of failure events is large and Weib. β parm. of PM dist. not = 1 or Weib. β parm. of CO dist. not = 1 and PM cycle length is not variable Then No model is suitable - explain</td>
<td></td>
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<table>
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<tr>
<th>RULE 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>If None of the above rules is successful Then No model can be applied - explain</td>
</tr>
</tbody>
</table>

Figure 2.6 Model Selection Rulebase for Prototype IMOS (49)
CHAPTER 3
METHODOLOGY AND SCOPE

3.1 Overview

The primary objective of the developed PC-based system is to automate the implementation of RCM through the integration of distinct techniques which have been postulated by experts in the field as noted in the published literature. This knowledge encapsulation process had to be carried out systematically to consider all of the different key factors in the analysis. Therefore, the first step in addressing this problem consisted of an exhaustive literature search to determine the most suitable mathematical and heuristic PM approaches to be consolidated into the system. This library research also provided valuable insights for developing fuzzy reasoning mechanisms to be included into the inference engine of the created system. From this analysis, the initial set of inference rules were constructed, the system architecture defined, and the user interface requirements identified. The formal knowledge representation was then translated into the selected development tool. The final step of the project implied the assessment and evaluation of the system’s performance as an effective RCM management tool.

3.2 Scope of the Research

The main purpose of the completed study was the development of a computer-based expert system to assist in RCM applications. Mainly, the system was designed to provide the industrial practitioner with an availability structure model of his process machines, which represents the foundation of the component risk assessment analysis.
The success of an RCM program greatly depends on the assessment of the multiple functional interdependencies among the individual system's component failure modes, as well as their corresponding criticality analyses. If the analyst lacks sufficient expertise for uncovering such component dependencies, the resulting RCM effort will be incapable of revealing critical factors or circumstances that if not properly considered in the analysis, make the development of a comprehensive and effective equipment maintenance program impossible. Nevertheless, for large industrial systems where the degree of complexity is such that most analysts can not conceive of all the distinct component interdependencies, an intelligent computer system with relevant knowledge on the system's functional characteristics would represent an important tool for constructing the required availability structure model.

The scope of this work focused on the development of a prototype expert system which could implement the RCM framework, using the chemical process industry as the application area.

3.2.1 The Chemical Process Industry

Chemical processes play a critical role in human society since they represent one of the most important manufacturing activities. The importance of this type of industry is easy to visualize- chemical products are everywhere. According to the literature, the chemical industry uses the greatest amount of engineering techniques and equipment among all industrial disciplines (98); therefore, it represents an appropriate application area for reliability management methodologies such as RCM.

The Office of Statistical Standards defines chemical and allied products as comprising three general classes of goods (66);
1. basic chemicals such as synthetic fibers, plastic materials, dry colors and pigments,

2. finished chemical products to be used for ultimate consumption as drugs, cosmetics, and soaps, and,

3. materials or supplies in other industries such as paints, fertilizers, and explosives.

Although, the manufacturing processes followed in the production of such items involve a wide variety of chemical procedures (ie. crystallization, evaporation, distillation, etc.), they are usually very similar and often only few variables are altered. Hence, since related engineering principles or techniques are usually applied, most of the manufacturing equipment used in different chemical plants ends up being very similar, if not identical.

Equipment maintenance is a key issue in this type of industry. Chemical processes are characterized by tight operational specifications which are clearly dependent upon the normal functioning of the different machines, thus, equipment reliability becomes a crucial factor in the overall process planning function.

Chemical engineers commonly use computer aided design (CAD) software to design, control, and monitor their industrial processes. Among such packages, ASPEN Plus, from Aspen Tech, has been adopted by leading chemical process companies, such as Dow, BASF, DuPont, and Exxon, as the industrial standard for the designing, and monitoring of chemical manufacturing systems. This package aims at the improvement of chemical operations by assisting the user in three major areas: process layout, equipment trouble shooting, and equipment design and rating capabilities. ASPEN Plus
is controlled through a graphical interface which allows the user to model a process by creating a process flowsheet, and then specifying the operating conditions (temperature, pressure, etc.) for each one of the system components. Once a base model for the process is specified, the user can run a simulation of its functioning, and perform a what-if sensitivity analysis to evaluate the effects of different operating scenarios. ASPEN Plus also assists the user in equipment cost estimation, process economic evaluation, and process optimization. This software is equipped with special modules for specific applications such as a petroleum and distillation enhancement subsystem, and an electrolytes expert system. At any time, the user can export the process flowsheet and layout drawings to a design program such as AutoCAD or any other CAD package (as a PXF file), or the equipment operating data and process simulation results to a computer spreadsheet (as a LOTUS file).

3.2.2 The New RCM Framework

This research was oriented to the development of a new automated RCM framework that ultimately can be viewed as a component of a new innovative computerized equipment maintenance environment. Figure 3.1 depicts the intended reliability management environment, whose final goal is the generation of optimal equipment maintenance strategies according to the type of manufacturing process and operating conditions of the plant.

Normally, chemical processes are highly complex. Their design, development, and control involve such a vast effort that engineers must use sophisticated computer software. In order to facilitate and minimize the user data input and intervention, the conceived maintenance environment directly utilizes the equipment condition and
operational data generated by ASPEN Plus as the main input for the RCM module. This module is embodied by the developed expert system, which generates the Availability Structure Model to be utilized by a Statistical Data Analysis Module.

The RCM component involves the accomplishment of three major tasks. First, the RCM module interfaces with ASPEN Plus and is able to recognize the distinct pieces of equipment and type of chemical process under analysis. Second, it determines all the different failure modes associated with the involved manufacturing equipment, how they may affect each other, and how they may obstruct the normal functioning of the overall system. Finally, the RCM module generates an availability structure model that could serve as the basis of the risk assessment analysis needed for determining the most beneficial equipment maintenance actions and strategies for the plant.

Figure 3.2 shows an example availability structure model. Such a model consists of a special type of reliability diagram or network which not only depict the different interdependencies among the system’s components, but also depicts associated equipment maintenance times (outside the scope of this study) as well as relevant data on how to handle possible failures of individual pieces of equipment. The main function of an availability structure model is to provide a framework for analyzing distinct failure scenarios via Monte Carlo simulation. Thus, a comprehensive availability structure model should include the following:

1. What should and should not be expected when a specific component fails?
2. How is the safety and normal operation of the plant affected when the component fails?
Figure 3.1 A Proposed Industrial Equipment Reliability Management Environment
3. What can and can not be done while maintenance is performed on the component?

4. For how long can the production process remain stopped, while the component is being repaired or replaced, without experiencing any considerable production loss?

5. What sort of immediate actions must be taken upon the occurrence of the failure?

3.3 The Knowledge Engineering Phase

3.3.1 Process Selection

The first step in the development of the expert system was the selection of a set of representative industrial chemical processes that could be used for extracting the needed equipment maintenance expertise.

Ten industrial process were selected on the basis of commercial importance. According to the 1992 Survey of Industrial Chemistry (14), the following (presented in order of importance) are the most produced industrial chemicals in the world; and hence, their production processes were taken as the main sources of the expertise used in this research.

3.3.1.1 Sulfuric Acid; H₂SO₄

Ninety nine percent of sulfuric acid is produced through the Contact Process, which was developed in England in 1831. In a Contact plant, sulfur and oxygen are burned to SO₂ at 1,830 °F, and then cooled to 788 °F. The SO₂ and O₂ then enter a converter containing four layers of catalyst, usually vanadium in the form of individual pellets. About 65% of
Figure 3.2 A Simple Availability Structure Model

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the SO₂ is converted to SO₃ in the first layer with a 2 to 4-second contact time. The gas which leaves the first layer at 1,112 °F is cooled to 752 °F and enters the second layer of catalyst. After the third layer about 95% of the SO₂ is converted into SO₃. The mixture is fed to an initial absorption tower, where SO₃ is hydrated to H₂SO₄ with a 0.5 to 1% rise in acid strength in the tower. The mixture is then reheated to 790 °F and enters the four layer of catalyst which gives overall a 99.7% conversion of SO₂ to SO₃. The gas is cooled and then fed to a final absorption tower where it is hydrated to H₂SO₄ (14, 21, 23, 45).

3.3.1.2 Nitrogen and Oxygen; N₂, O₂

There are three fundamental steps in the production of oxygen and nitrogen from the liquefaction of air: purification, refrigeration, and rectification. Purification is the removal of dust, water, vapor, carbon dioxide, and hydrocarbon contaminants through an oxidation chamber. Refrigeration in an oxygen plant means cooling the compressed air (at approximately 77 psi) until it becomes a liquid at about 310 °F below. Rectification is the separation of liquid air into its components, oxygen and nitrogen by repeated distillation (14, 16, 55, 65).

3.3.1.3 Ethylene and Propylene

Most ethylene and propylene is made by the thermal cracking, sometimes called steam cracking of hydrocarbons at high temperatures with no catalyst. The feed streams (ethane and propane) are first mixed with steam and then cracked in separate furnaces at temperatures ranging from 1,150 to 1,500 °F. The combined effluents are water-scrubbed and cooled to 100°F to condense polymers and aromatics. Ethylene and lighter hydrocarbons are removed in a fractionating column called deethanizer, and leave in the
overhead product stream. The bottom stream contains propylene and higher hydrocarbons. Recovery of the ethylene is carried out by cooling the overhead stream to about -195°F and treating the condensed liquid in another fractionating column called a demethanizer. The bottom product from the demethanizer is fed to an ethylene fractionator for purification. Recovery of the propylene involves treatment of the bottoms from the deethanizer in a depropanizer (another fractionating column) and a propane splitter (14, 64, 81, 89, 98).

3.3.1.4 Calcium Oxide or Lime; CaO

During the production of lime, limestone is crushed and screened to a size of approximately 4 to 8 in. The limestone then passes through a kiln which in most cases is a gas-fired upright kiln where the stones burn at different rates according to their sizes. Once the lime product leaves the kiln, it is cooled in rotary air-fluidized cylinders, and sent to a slaker if slaked (Ca(OH)₂) is desired (14, 66, 85).

3.3.1.5 Ammonia; NH₃

Ninety percent of ammonia plants generate the hydrogen required for the ammonia manufacture by steam-reforming of natural gas. Desulfurized natural gas is fed with steam to a primary reformer, where it is reacted with steam in Ni-catalyst-filled tubes. The reformed gas and steam are then cooled to 700°F. This cooled gas-steam mixture enters a two-stage shift converter where iron and cooper catalysts are employed to obtain raw synthesis gas. This synthesis gas, after being purified in CO₂ absorbers and strippers, is then compressed in a two-case centrifugal compressor. Interstage cooling is provided by heat exchange with methanator feed, cooling water, and NH₃ refrigerant. Anhydrous
ammonia is catalytically synthesized in a loop in which unconverted gas is recycled for eventual conversion to ammonia (14, 16, 55, 108).

3.3.1.6 Phosphoric Acid; $\text{H}_3\text{PO}_4$

By 1989, 91% of the world's production of phosphoric acid was made by the Wet Process. In this process, the phosphate rock is ground and mixed with dilute $\text{H}_3\text{PO}_4$ in a mill. Then, the mixture is transferred to reactors where $\text{H}_2\text{SO}_4$ is added. The reactors are heated to around 175°F for 4 to 8 hours. Air cooling carries the HF and SiF$_4$ side products to an absorber tower which transforms them into H$_2$SiF$_6$. Filtration of the solid gypsum (CaSO$_4$, 2H$_2$O) from the reactors gives the final dilute H$_3$PO$_4$ solution (14, 64, 65, 89).

3.3.1.7 Caustic Soda and Clorine; $\text{NaOH, Cl}_2$

In 1892 the electrolysis of brine was discovered as a method for making both sodium hydroxide and chlorine. This rapidly grew in importance and since the 1960s it has been the only method of manufacture. In the electrolytic process, the brine (25% NaCl solution) is first purified, and then sent to an electrolytic cell where Cl$_2$ and H$_2$ are precipitated. Two types of cells are commonly used, the diaphragm cell used now in 78% of all production plants, and the mercury cell which is employed in 19% of the plants. Evaporation and filtration of the basic solution after electrolysis yields a solid salt, which can be recycled, and an industrially 50% caustic soda solution (14, 66, 81, 108).

3.3.1.8 Sodium Carbonate or Soda Ash; $\text{Na}_2\text{CO}_3$

Although during the last years there has been a tremendous conversion from synthetic to natural soda ash consumption, the Solvay method for manufacturing soda is still very popular world wide. Sodium carbonate is made from a NaCl brine that is mixed with
ammonia in a large ammonia absorber. A line kiln is also employed as the source of carbon dioxide, which is mixed with the salt and ammonia in carbonation towers to form ammonium bicarbonate and finally sodium bicarbonate and ammonium chloride. After filtration, the sodium bicarbonate is heated to 350°F in rotary dryers to produce light soda ash. Dense soda ash, used by the glass industry, is manufactured from light ash by adding water and drying. Normally, the ammonium chloride solution goes to an ammonia still where the ammonia is recovered and recycled (14, 45, 64, 81, 89).

3.3.1.9 Nitric Acid; HNO₃
In the latter years, nitric acid is only manufactured by direct oxidation of ammonia. A high-pressure process is most often used where the ammonia is fed to a reactor containing a rhodium-platinum catalyst at 1,380 to 1,690°F and 100 psi. From the reactor, a mixture of NO and O₂ is cooled, and transferred to an absorption tower with water and air to oxidize the nitric oxide and hydrate it to around 65% nitric acid in water. This nitric acid solution is later concentrated in a silicon-iron or stoneware tower containing 98% sulfuric acid which yields, as final products, 90% nitric acid off its top and 75% sulfuric acid as its bottoms (14, 55, 65, 89).

3.3.1.10 Ammonium Nitrate; NH₄NO₃
Although the basic reaction is the same, the manufacture of ammonium nitrate greatly varies from plant to plant. Crystals, granules, and prills are made with the same chemistry but different engineering. In this study, the prilling technique was adopted. In a stainless steel reactor, a mixture of NH₃ and 60% NH₄NO₃ is concentrated to 85% nitrate. Posterior vacuum evaporation at 260 to 285°F further concentrates the solution to 95%. This hot solution is then pumped to the top of a spray or prilling tower 195 to 230 feet
high. It is discharged through a spray head and solidifies as it falls in the air to form small spherical pellets of 0.08 in diameter. The prills are screened, further dried, and dusted with clay to minimize sticking (14, 16, 55, 85, 89, 98).

3.3.2 The Pieces of Equipment Considered in this Study

From the previously mentioned chemical processes, sixty two different industrial process machines were identified, and their most relevant failure modes extracted from the pertinent literature and field experts. Appendix A shows these sixty two pieces of equipment as well as their corresponding failure modes. Nevertheless, for the development of the expert system, a subset of eleven of such machines was selected on the basis of extent of use in the industrial settings. The eleven pieces of equipment selected are the following:

- Burner
- Centrifugal Blower
- Centrifugal Pump
- Compressor
- Converter
- Distillation Tower
- Evaporator
- Heat Exchanger
- Pipeline
- Reactor
- Waste Heat Boiler
3.3.2.1 Burner

The type of chemical burner considered in this research is a full-cone spray burner provided with a low-pressure air-atomizing nozzle. This type of burner has a maximum fuel atomizing capacity between 30 and 35 short tons a day, and it requires between 550 and 750 std. ft³ of air per minute at a maximum pressure of 4 psi.

As it can be seen in Figure 3.3, the burner consists of three major components: a centrifugal pump, a centrifugal blower, and a combustion chamber. The combustion chamber is made out of a 3/8 in. steel plate lined with 4 ½ in. insulating and 9 in. fire brick. Its internal production volume is estimated to be between 20 and 25 ft³/short ton a day. The spray nozzle is assumed to be of carbon steel.

3.3.2.2 Centrifugal Blower

Figure 3.4 depicts the type of centrifugal blower assumed in the construction of the expert system. It represents a centrifugal blower capable of developing pressure between 1 and 4 psi. It has a steel housing and stainless steel wheel with rubber internal seals. This type of blower has a maximum capacity between 8,000 and 11,000 ft³ per minute, which implies a 100 to 250 hp blowing motor.

3.3.2.3 Centrifugal Pump

Single-stage, enclosed impeller centrifugal pumps represent the type of pumps considered by the developed expert system. This kind of pump can discharge between 100 and 300 gallons per minute with a total head (discharge head plus suction head) of 225 to 650 feet, and a maximum speed between 3,000 and 4,500 rpm.

The common dimensions for a medium single-stage pump imply a 1½ to 3½ in suction diameter, a 1 to 3 in. discharge diameter, a 5 to 7 in. impeller diameter, and a ½ to
¼ in. impeller width. Their casings and impellers are most frequently made out of cast iron, the shaft and wearing rings of stainless steel, and the mechanical seals of carbon resin and nitrile. A single-stage, enclosed impeller pump is shown in Figure 3.5.

3.3.2.4 Compressor

The expert system was designed to handle medium-sized multistage centrifugal compressors. As it can be seen in Figure 3.6, this type of compressor has 3 to 5 stages made out of stainless steel impellers, shafts, and diaphragms.

The maximum inlet capacity for the type of compressors considered in this project is between 20,000 and 30,000 ft³ of gas or air per minute, which implies a 400 to 600 hp driving motor.

3.3.2.5 Converter

The type of gas converter covered in this project is the four-stage fluidized-bed reactor with two internal heat exchangers for gas cooling. Such a converter consists of a single cylindrical cast iron shell, with chrome cast-iron catalyst supporting grids, and steel heat exchanger tubes. The catalysts here assumed to be used in this type of converter are platinized magnesium sulfate and vanadium oxide.

A medium-size range of converters has been adopted. Thus, the inside diameter of the studied type of converter is around 6 feet, 12 feet high, 9 to 12 in. the depth of catalyst on each one of the four shelves, and a catalyst load averaging 1,500 lb per tray. Moreover, the converters are assumed to be equipped with internal heat exchanger tubes of 1 to 2 in. of inside diameters in a 6 to 7 in. steel shell. Figure 3.7 depicts a typical gas converter configuration used in the knowledge engineering phase of this project.
3.3.2.6 Distillation Tower

The two-bed packed distillation tower was adopted in this research. Such a column consists of ceramic “Raschig” rings that allow the distillation of two products at a time inside the column. The tower is assumed to have an operational pressure ranging between 250 and 350 lb/ft², and its height are thought to be between 35 and 40 feet, with an inside diameter of 4 to 6 feet.

Regarding the supporting bar grids inside the column, they were to be ¼ in thick bars spaced 1¼ in from each other. Figure 3.8 illustrates the common structure of a “Rashing”-ring packed distillation tower.

3.3.2.7 Evaporator

One of the most popular types of evaporators found in the industry is the forced-circulation evaporator with external horizontal heating surface. This type of evaporator consists of a centrifugal pump that circulates the fluid to be concentrated throughout the apparatus, an external tubular heat exchanger which heats the circulating fluid with the heat provided by hot steam running in its shell side, and a steel vapor head through which the vapor of the solution is dissipated.

The developed expert system was designed to handle forced-circulation evaporators with a vapor head of 10 to 15 feet of height, and 7 to 10 feet inside diameter. Furthermore, the heating tubes were thought to have a length between 8 and 10 feet with inside diameters ranging between ¾ and 1 ¼ in. Figure 3.9 depicts a typical forced-circulation evaporator.
Figure 3.7 Converter (21)
Figure 3.8 Distillation Tower (78)
3.3.2.8 Heat Exchanger

Figure 3.10 shows a typical shell-and-tube heat exchanger. In this project, a two-pass, floating-head, shell-and-tube heat exchanger was chosen as the standard for the knowledge base of the developed system. In this type of exchanger, cold liquid travels through the inside tubes while hot fluid, gas, or steam runs throughout the cover shell. Usually, welded steel is used as construction material for the cover shell of the apparatus, while stainless steel is the choice for the inside tubes.

The heat exchangers have between 80 and 200 tubes of nominal diameters between \( \frac{3}{4} \) and \( 1\frac{1}{4} \) in. with a 6:1 ratio of tube length to shell diameter.

3.3.2.9 Pipeline

There are literally hundreds of pipeline types employed in the chemical industry to transport multiple kinds of fluids and gases. As it was impossible to address all of them here: only pipelines for low pressure gas and low pressure fluid were considered in the expert system.

For low pressure gas, it is assumed a pipeline of butt-welded wrought iron is used, capable of standing pressures not exceeding 500 psi, and temperatures lower than 500 °F. Such a pipeline is \( \frac{3}{8} \) to 3/8 in. thick and 3 to 6 in. of inside diameter, permitting a maximum span of 15 to 21 feet between supports. For low pressure fluid, it is assumed a api-welded galvanized wrought iron pipeline, capable of standing a maximum pressure of 200 psi, and temperatures not higher than 450 °F. The pipeline dimensions are the same as the ones for the low pressure gas pipeline, although the permissible span between supports was specified between 12 and 17 feet.
Figure 3.9 Forced Circulation Evaporator (5)

Figure 3.10 Tubular Heat Exchanger (27)
Regarding pipe support hardware and fittings, wrought iron brackets were considered as roof and wall supports while brick pier support rollers as floor supports. The pipe fittings were assumed to be screwed or flanged, made out of cast iron, and capable of operating under pressures of up to 500 psi, and temperatures lower than 750°F. Figure 3.11 exemplifies the types of pipe support hardware included in the research.

3.3.2.10 Reactor

The batch, liquid-to-liquid, closed-vat with stirrer reactor illustrated in Figure 3.12 represents the class of reactors incorporated into the knowledge base of the expert system. ASTM AS88 grade B steel is commonly used in the manufacturing of such reactors, which have with 2 to 4 radial-bladed paddle agitators, capable of generating 50 to 100 rpm.

The reactor size considered here are between 7 and 13 feet high, an internal vat diameter of 6 to 10 feet, a total length of the paddle impeller between 60 and 70% of the inside diameter of the vessel, and a blade width equal to one seventh of its length.

3.3.2.11 Waste Heat Boiler

Figure 3.13 depicts a kettle waste-heat boiler normally used in medium-sized factories for water heating or steam generation. Such boilers consist of stationary water contained in the kettle while a hot fluid, heated by either liquid or gas, runs inside the tubes. Stainless steel is generally used for both the shell and tubes of the boiler, which under normal operating conditions can generate between 30,000 and 50,000 lb/hr of 100 to 150 psig steam.
Figure 3.11 Fluid and Gas Pipeline (70)

Figure 3.12 Closed Vat Reactor (78)
Figure 3.13 Waste Heat Boiler (64)
3.3.3 Data Recollection on Failure Modes

For each of the eleven chosen pieces of equipment, their most relevant failure modes were obtained as explained in the previous section. Pertinent literature was reviewed, and human experts were consulted, when needed. The library sources used for information on the different failure modes are listed in the references.

In general, the information can be divided into two major groups. The first type of data was that related to the impact (at the local and system levels) of the specific failure mode. The second type deals with the possible factors generating or precipitating the failure mode in question.

3.3.3.1 Failure Modes Effects and Controls

Appendix B contains all the information regarding the local and system effects as well as suggested controls for each one of the eighty failure modes identified in this research.

The local effects are those consequences associated with the failure of normal functioning of the particular piece of equipment. Such locals effects also cover the likelihood or possibility of other failure modes (for the same machine) being precipitated or aggravated by the failure mode in question. System effects deal with the consequences at a global level, including the impact that the failure mode has on the functioning and condition of nearby equipment as well as the quality of the final or intended product. Other considerations such as noise and vibration contamination, as well as human hazards are also included in the system effects. Finally, a list of potential preventive controls such as visual inspection, and other specialized diagnosis tests were included in the study to complement and enhance the final report to the user.
The local and system effects provide informative maintenance data to the industrial practitioner, but also are critical criteria for the development of the failure mode prioritization essential in any RCM program.

3.3.3.2 Factors Responsible for Failure Mode Precipitation

The most important, as well as the most time consuming, endeavor during the knowledge engineering phase of this project was the identification of the factors thought to be the most relevant causes for the precipitation and aggravation of each one of the eighty failure modes considered by the developed expert system.

For each of the eleven machines covered in the study, the corresponding literature sources were examined and reviewed in detail, distinguishing for every particular failure mode three classes of precipitating factors:

- Factors considered to have a critical effect in the development of the specific failure mode. Those were named the “critical factors”.
- Factors considered to have an important inherence in the development of the specific failure mode. Those were named the “important factors”.
- Factors considered to be somehow related to the development of the specific failure mode. Those were named the “related factors”.

For any of the identified factors, critical, important, or related, proper limits were established in order to assess the magnitude of their impact on the evolution of the different failure modes. For instance, if for a multistage centrifugal compressor, the rotor speed was found to be an “important” factor for the deformation of the compressor’s thrust bearings, and lower and upper limits of 3,000 and 20,000 rpm were set
respectively, it would then be implied that for rotor speeds below 3,000 rpm, no significant impact on the thrust bearings should be expected while for speeds of 20,000 rpm or higher, a maximum impact on the deformation of the thrust bearings is certain.

All critical, important, and related factors identified in this research as well as their corresponding magnitude limits are listed in Appendix C. The way in which that information was used for predicting the likelihood of the precipitation of a particular failure mode under determined working conditions is discussed in the following section.

3.4 The Mathematical Formulation of the System

After reading the process flow chart generated in ASPEN Plus, the expert system performs two major tasks. It first evaluates all the failure modes involved in the different machines of the process under scrutiny, detecting those that are likely to precipitate according to the existing working conditions (called screening); and then prioritizes them according to the risk that they pose to the system, the working environment, the operators, and the product being manufactured.

3.4.1 Failure Mode Screening

The failure mode screening methodology developed during this research is based upon the fuzzification of the effect of the precipitating factors shown in Appendix C. An approximate reasoning algorithm, consisting of a fuzzy mathematical formulation which relates the presence of one or more precipitating factors to the development of a specific failure mode, was created to enable the inference mechanism of the expert system to determine those failure modes that should be included in the final RCM analysis.

For each failure mode, three different types of precipitating factors were defined: critical, important and related factors. A critical factor is a situation which impact on the
development of a failure mode can be catalogued as determinant. A critical factor differs from important and related factors in the sense that its full presence, that is when its magnitude goes beyond its most extreme limit, guarantees the precipitation or development of the related failure mode. An important factor is that whose contribution in the development of the failure mode is substantial although not determinant. A related factor, on the other hand, is a condition that has been identified with the development of a failure mode, although its contribution can not be considered as significant.

All identified precipitating factors were expressed as trapezoidal fuzzy numbers so that their contribution to the development of a particular failure mode of interest could be quantified as fuzzy numbers between 0 and 1. Let \( f_a \) be defined as the trapezoidal fuzzy number representing precipitating factor \( a \) for a particular failure mode, then:

\[
f_a (x) = \begin{cases} 
0 & \text{if } x \text{ does not reach the magnitude limits} \\
mx + b & \text{if } x \text{ lies between the magnitude limits} \\
1 & \text{if } x \text{ lies beyond the magnitude limits}
\end{cases}
\tag{3.1}
\]

where \( x \) is the current numeric value of factor \( a \), and \( mx + b \) denotes a linear equation which increases from 0 to 1 as \( x \) goes from the less critical magnitude limit to the most critical one.

Trapezoidal numbers of distinct shapes can be constructed from the fuzzification of the different precipitating factors since the nature of the magnitude limits will determine the slope of the resulting numbers. For instance, if for a tubular heat exchanger the following precipitating factors for "plugged or fouled tubes" have been defined:
Factor a: High temperature of shell substance \(150^\circ \text{F} \text{ to } 800^\circ \text{F}\)

Factor b: Low cross flow velocity on shell \(15 \text{ to } 3 \text{ feet/second}\)

Factor c: Acidity or basicity of shell substance \(\text{pH: } 0 \text{ to } 4 \text{ or } 10 \text{ to } 14\)

then, the corresponding fuzzy trapezoidal numbers for factors a, b, and c in accordance to their magnitude limits would be:

\[
f_a(x) = \begin{cases} 
0 & \text{if } x \leq 150^\circ \text{F} \\
0.0015x - 0.23 & \text{if } 150^\circ \text{F} < x < 800^\circ \text{F} \\
1 & \text{if } x \geq 800^\circ \text{F}
\end{cases} \quad (3.2)
\]

\[
f_b(x) = \begin{cases} 
0 & \text{if } x \geq 15 \text{ ft/s} \\
-0.083x + 1.25 & \text{if } 15 \text{ ft/s} > x > 3 \text{ ft/s} \\
1 & \text{if } x \leq 3 \text{ ft/s}
\end{cases} \quad (3.3)
\]

\[
f_c(x) = \begin{cases} 
0 & \text{if } 4 \leq x \leq 10 \\
-0.25x + 1 & \text{if } 4 > x > 0 \\
0.25x - 2.5 & \text{if } 10 < x < 14 \\
1 & \text{if } x = 0 \text{ or } x = 4
\end{cases} \quad (3.4)
\]

As it can be seen in Figures 3.14, 3.15 and 3.16, the resulting trapezoidal numbers differ in their basic shapes; however, their feasible values will always be between 0 and 1.

Having illustrated how the fuzzification of the different precipitating factors is carried out, the approximate reasoning algorithm devised for screening a particular failure mode according to its likelihood of development is stated as follows:

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1. Evaluate all precipitating factors for the failure mode under scrutiny, $f(x)_{factor \ i}$, according to the values given by the analyst. This would fuzzify the effect that critical, important, and related factors have on the precipitation of the failure mode.

2. Compute the following Likelihood Coefficient:

$$LC = w_{cr} \sum_{\forall \ i = \text{critical}} f(x)_{factor \ i} + w_{im} \sum_{\forall \ j = \text{important}} f(x)_{factor \ j} + w_{re} \sum_{\forall \ k = \text{related}} f(x)_{factor \ k} \quad (3.5)$$

where, $w_{cr}$, $w_{im}$, and $w_{re}$ are the selected weights for the critical, important, and related factors involved in the development of failure mode $i$, respectively.

3. Compare the computed Likelihood Coefficient ($LC$) against the predetermined threshold for failure mode $i$, $Th_{ri}$. If $LC$ is greater than $Th_{ri}$, then failure mode $i$ should be included in the final RCM analysis, otherwise, discard failure mode $i$ from the maintenance program.

It should be indicated that this failure mode screening algorithm is executed only if all critical precipitating factors values are below their corresponding extreme limits. That is, if one (or more) critical factor for a specific failure mode has reached or gone beyond its most critical magnitude limit, the failure mode in question will be considered to be worthy of being included in the final RCM analysis, making computation of its Likelihood Coefficient unnecessary.

Regarding the weights for each type of factor, their selection should be consistent with the nature of the expertise being encoded in the knowledge base. For instance, for the developed expert system, $w_{cr}$, $w_{im}$, and $w_{re}$ were defined as 3, 2, and 1, respectively.
Figure 3.14 Fuzzification of Factor "a"

Figure 3.15 Fuzzification of Factor "b"
Figure 3.16 Fuzzification of Factor "c"
since a critical precipitating factor was thought to contribute 1.5 times more to the
development of a failure mode than an important factor; and an important factor was
assumed to have a failure mode precipitating impact twice as big as that of a related
factor.

The threshold value for a failure mode should represent the minimum amount of
"evidence" that the analyst is willing to accept regarding the prompt manifestation of the
failure mode. This "evidence" is directly associated with the magnitude of the impact of
distinct precipitating factors provoking the failure mode. During this research, a
threshold value of 5 was selected for all the 80 failure modes considered in the
knowledge base. This Thr value is equivalent to the evidence of a fully presented
\( f(x) \) critical precipitating factor, along with the full presence of an important
factor \( (w_{cr} \cdot f(x) + w_{im} \cdot f(x) = 3 \cdot 1 + 2 \cdot 1 = 5). \) Although in this project
all Thr's were assigned the same value, this may not always be the case; and another
knowledge domain application may require the selection of distinct Thr values for
different failure modes.

To illustrate how this algorithm is applied by the expert system, the previous
example of the plugged or fouled tubes of a tubular heat exchanger is examined again, but
this time it is assumed that such a failure mode involves one critical precipitating factor,
two important factors, and one related factor as following defined:

**Critical Factor 1:** High temperature of shell substance \( \{150 \text{ °F to 800 °F}\} \)

**Important Factor 1:** Low cross flow velocity on shell \( \{15 \text{ to 3 feet/second}\} \)
Important Factor 2: High liquid viscosity on shell \{100 to 700 SSU\}

Related Factor 1: Acidity or basicity of shell substance \{pH: 0 to 4 or 10 to 14\}

The fuzzicization of critical factor 1, important factor 1, and related factor 1 were given in equations 3.2, 3.3, and 3.4, respectively. The fuzzy trapezoidal number for important factor 2 is determined by the expression:

\[
f_{imp,\text{fact.2}}(x) = \begin{cases} 
0 & \text{if } x \leq 100 \text{ SSU} \\
0.0016x - 0.16 & \text{if } 100 \text{ SSU} < x < 700 \text{ SSU} \\
1 & \text{if } x \geq 700 \text{ SSU}
\end{cases}
\] (3.6)

Now, if during the consultation, the shell fluid was found to be at 300°F, traveling at 12 ft/s, with a viscosity equal to 650 SSU, and a pH of 3; then the resulting Likelihood Coefficient of the failure mode under analysis would be:

\[
LC = w_{cr} f(x)_{\text{factor 1}} + w_{im} (f(x)_{\text{factor 1}} + f(x)_{\text{factor 2}}) + w_{re} f(x)_{\text{factor 1}}
\]

\[
LC = 3 \times 0.23 + 2 \times (0.25 + 0.92) + 1 \times 0.25
\]

\[
LC = 3.28
\]

Since the computed value of \(LC\) is lower than the threshold value of 5, this particular failure mode would not be included in the final system recommendation. It should be clear that had the fluid temperature been 900°F instead of 300°F, the failure mode would have automatically been included in the final RCM analysis report without any further computation since the shell temperature had been catalogued as a critical factor and 900°F goes way beyond the critical magnitude limit of 800°F.
3.4.2 Prioritization of Failure Modes

As was discussed in Chapter 2, not all failure modes are created equal, and this understanding is what distinguishes RCM from other reliability management methodologies. The expert system carries out the prioritization of the failure modes that pass the screening phase by assessing the overall risk involved in their precipitation. This risk assessment analysis is not performed through the use of a decision tree as the traditional RCM framework usually implies; rather, a fuzzy linguistic scheme was created to combine practical expertise and possibility theory in the categorization of equipment failure modes.

The impact of any failure mode can be evaluated from three different effect levels:

- The Local Level. At this level, the consequences of a failure mode are examined according to the repercussions on the normal functioning of the machine suffering from the failure, as well as the possibility that other failure modes could result in the same piece of equipment as a result of a chain effect.

- The Product Level. At the product level, a failure mode is analyzed on the basis of how badly the product in process is affected by its development. Here, global effects such as system shutdowns, working environment conditions, and safety considerations become important issues at the time of evaluating the failure mode since they have a direct influence on the quality of the final product.

- The Secondary Failure Level. At this level, all possible repercussions in other pieces of equipment are analyzed and evaluated. There are two types of
secondary failures, those that are related to nearby process machines, and those that are associated with downstream equipment. Thus, when examining secondary failures, it is of interest to assess all potential functional failures caused by a particular failure mode in other pieces of equipment that are placed upstream and downstream in the process arrangement.

The developed prioritization scheme was designed having in mind all these three levels of effects, as well as the Likelihood Coefficient discussed in Section 3.4.1. The local and product level effects can be determined directly from expertise withdrawn from library sources and human experts since they are simply an estimate of how badly a particular machine failure could affect its normal operation and the product being manufactured. Regarding secondary failures, their assessment it is not as simple, since it is not only necessary to know the nature of the damage that a specific failure mode could have in related and nearby machines, but also the type and the physical arrangement of the pieces of equipment upstream and downstream of the machine presenting the failure.

The prioritization scheme involves the computation of the Priority Index for each failure mode included in the final RCM analysis, that is, those that pass the screening phase. The Priority Index ($PI$) is defined by the following expression:

$$PI = LI \times LEI \times PEI \times SFI$$  \hspace{1cm} (3.8)

where $LI$ is the Likelihood Index, $LEI$ is the Local Effects Index, $PEI$ is the Product Effects Index, and $SFI$ is the Secondary Failures Index.

For this project, $LI$, $LEI$, $PEI$, and $SFI$ were defined in such a way that each one of them can take a value between 1 and 4. Therefore, the Priority Index of any failure mode
can range from 1 (which would imply that the failure mode is just important enough to be considered in the maintenance program of the plant) to 256 (which would indicate that the failure mode is excessively critical and deserves all the possible attention and efforts from the maintenance practitioner for its control or redesign).

3.4.2.1 The Likelihood Index

The Likelihood Index is simply a measure for comparing the threshold value \((Thr)\) of a particular failure mode against its Likelihood Coefficient. Thus, the Likelihood Index is defined as:

\[
LI = \frac{LC}{Thr}
\]  

(3.9)

In essence, the Likelihood Index indicates how many times the Likelihood Coefficient of a failure mode went over its pre-established threshold value during the screening phase included in the final maintenance program. As mentioned before, for this study a \(Thr\) of 5 was chosen for each one of the eighty failure modes considered in the knowledge base, and since the highest possible \(LC\) turned out to be 20, in this particular application \(LI\) can only take a value between 1 and 4.

3.4.2.2 The Local and Product Effects Indices

Both the Local and Product Effects Indices are obtained directly from the sources of expertise. They are just a measure of the impact that a failure mode could have on the specific machine where it originates and on the product.

Such indices were defined according to the following scheme: for a particular failure mode, a \(LEI\) of 1 was assigned if its potential local effects were found to be small.
a value of 2 if they were catalogued as considerable, 3 if they were thought to be large, and 4 if they were regarded as extremely detrimental. The same scheme applies to the PEI.

Appendix C depicts the assigned values for LEI and PEI for all eighty equipment failure modes covered in this research. It should be stressed again that the assignment of such values are entirely based on the expertise drawn from relevant literature (see references). Therefore, the accurateness and validity of such indices depend exclusively on the quality of the knowledge engineering phase.

3.4.2.3 The Secondary Failures Index

It is important to evaluate how a machine failure mode can impact other machinery located nearby or downstream in the process flow. The Secondary Failures Index represents a means for doing that, by taking into consideration the given arrangement of the production process, and the way in which the failure mode affects the involved pieces of equipment.

In this research the SFI was defined as:

$$SFI = 1 + 1.5 \times MaxNear + 1.5 \times MaxDown$$ (3.10)

where $MaxNear$ and $MaxDown$ are indicators of the impact that the failure mode has on nearby and downstream machines. Both of these indicators are determined according to two important estimators: (1) the magnitude of the nearby or downstream failure mode effects ($NMS$ or $DMS$ respectively), and (2) the nearby or downstream equipment susceptibility to the failure mode effects ($NES$ or $DES$). Thus, for a specific failure mode $MaxNear$ and $MaxDown$ are determined by the following expressions:
\[ \text{MaxNear} = \max \{ NMS_i \times NES_i \} \quad \forall \text{ nearby machines } i \] 

(3.11)

and,

\[ \text{MaxDown} = \max \{ DMS_j \times DES_j \} \quad \forall \text{ downstream machines } j \] 

(3.12)

A machine is considered to be nearby the current machine if they are attached to each other with no pipeline between them. A downstream machine is that which immediately follows the machine presenting the failure mode in the production process flow. However, since ASPEN Plus does not provide any information about the production process dimensions, a downstream machine that is connected to the equipment associated to the failure mode by a pipeline will be assumed not to be affected by the failure mode unless the effects of that failure mode are considered to be “flow transmitted”. In that case, the expert system will “skip” the pipeline, and carry out the \( DMS_j \times DES_j \) computations for all pieces of equipment connected to the pipeline. Appendix E contains the \( NMS, DMS, NES, \) and \( DES \) values assigned to each failure mode in relation to the type of nearby or downstream machine. It is also specified in Appendix E which failure modes have downstream effects that can be “pipeline transmitted”, and which do not.

The \( NMS, DMS, NES, \) and \( DES \) estimators were obtained directly from the available expertise, and the assignment of their values was carried out according to the following schemes:

- **For \( NMS \) and \( DMS \):**
  - 0.00 if there is no nearby or downstream consequences for that failure mode
  - 0.25 if nearby or downstream effects are small
  - 0.50 if nearby or downstream effects are considerable
  - 0.75 if nearby or downstream effects are large
  - 1.00 if nearby or downstream effects are excessively critical
• For NES and DES:
  0.00 if the nearby or downstream equipment is not affected by the failure mode at all
  0.25 if the nearby or downstream equipment is a little affected by the failure mode
  0.50 if the nearby or downstream equipment is considerably affected by the failure mode
  0.75 if the nearby or downstream equipment is largely affected by the failure mode
  1.00 if the nearby or downstream equipment is critically affected by the failure mode

The next chapter discusses the engineering design and development of the computer knowledge based system that was constructed to implement and deliver the RCM framework here described.
CHAPTER 4  
DESIGN AND DEVELOPMENT OF THE EXPERT SYSTEM

This chapter discusses the software and hardware platform used in the creation of the RCM expert system, as well as the system design approach followed during the implementation of the RCM framework explained in Chapter 3.

4.1 Knowledge Representation Paradigm

Once the information collected during the knowledge acquisition phase was reviewed and logically organized according to the developed framework, it had to be represented through the use of a paradigm embedded in the expert system. There are several paradigms that can be used to represent knowledge. Rules, frames or objects, networks, and logical predicates are among the most widely used. Rules represent the most popular of all representation schemes. They are If-Then statements which generate conclusions once the validity of specific facts (premises) has been verified (6). A frame consists of a set of slots that contains a group of specifications describing an object, action, or event (38). Semantic networks represent a group of nodes linked together to form object relationships. Predicate logic is a kind of formal logic which is used to make generalizations about propositions based on specific relationships (6).

Nevertheless, although the developer may find a wide range of options, it depends upon the nature of the knowledge involved which representation paradigm suits best the system specifications. The developed expert system was designed to access the likelihood of occurrence for a predetermined set of failure modes. In essence, the system is designed to store information associated with the precipitation of the failure modes.
involved in the process equipment under scrutiny. Once each precipitating factor is evaluated, the failure modes are screened through the use of an approximate reasoning scheme. It is then that the final Priority Index is computed for those failure modes found to be critical enough to deserve consideration.

Therefore, the system does not seek a specific goal or conclusion, as in the case of most rule-based systems where rules have specific premises designed to lead the reasoning process to one or another course of action. It utilizes the information contained in system classes (i.e. failure mode variables) to produce the final RCM output, which is based upon mathematical and heuristic computations.

Since the intended application involved the processing of exhaustive information on the relationship of equipment failure modes, causitive factors, and process arrangement, mutually associated in a heterogeneous way, object oriented programming was found to be the most appropriate paradigm. This does not mean that it was the only knowledge representation mechanism that could have been applied to this project. However, it proved to be efficient in satisfying the computing demands of this research.

4.2 Software and Hardware Platform

The constructed expert system was designed to work on a personal computer. The following reasons determined this decision:

1. Most companies utilize personal computers as a part of their office equipment. Thus, no extra expenses will have to be made for implementing the system.

2. The IBM compatible PC version of ASPEN Plus, the chemical process design software that is integrated with the developed knowledge based system, is the most commonly used.
3. The PC environment makes the system portable. It can be loaded onto a Laptop or Notebook microcomputer and be taken to the floor shop or to business strategy meetings.

4. PC-based systems can be developed in a windowing environment which made the expert system very friendly, and increased the aesthetics of its screens.

Therefore, the prototype knowledge base system was delivered on an IBM compatible Personal Computer with a Pentium processor, a base memory size of 16 MB, and a hard-disk space of 16 MB.

The software used in this project was selected on the bases of availability, and versatility in addressing the system requirements. The selected support and application software is listed as follows:

- Microsoft Windows 95
- LEVEL 5 Object release 3.6
- Microsoft Excel release 7.0

Since objects or frames constituted the chosen knowledge representation paradigm for this project, an object-oriented expert system shell, or conventional or symbolic language was needed to implement the system.

An expert system shell is a computer package capable of applying knowledge to a problem domain. Thus, a shell is a "reasoning" entity containing an empty knowledge base. A conventional language is a programming language used in conventional operating systems. It is designed to handle numerical operations only. On the other
hand, a symbolic language has built-in features to aid in building expert systems. It is primarily designed to handle symbolic processing computations (38).

In this research, a computer software shell was employed for the programming tasks due to the following two major reasons:

1. The use of a software shell facilitates the programming process, allowing the developer to spend more time on the knowledge engineering acquisition phase.

2. Since the developed system represents the initial version, a rapid prototyping approach was desired.

LEVEL 5 Object is an object-oriented tool with multiple inference strategies in a flexible windowing environment. It can be integrated with commercial software programs, and all conventional programming languages. It was mainly chosen because of its relatively low price, high quality graphics, and versatility in the processing of numeric computations. Moreover, the graphical user interface of LEVEL 5 Object allowed the importing of scanned bit-map files required for the graphical illustration needed in the system.

LEVEL 5 Object was interfaced with Microsoft Excel to access the process flowsheet data generated by ASPEN Plus. An ASPEN Plus user can export his application results as a Lotus 123 file, which can then be read by LEVEL 5 Object via Microsoft Excel.
4.3 System Architecture

Figure 4.1 depicts the architecture of the developed expert system. It consists of three major components which were constructed on a modular basis: the database, the heuristic base, and the output generator.

The database contains all the relevant information on the eleven chosen pieces of equipment. The data included in the database cover the equipment characteristics, local and system effects of each failure mode, their suggested controls, precipitating factors and corresponding limits, as well as the assigned $PEI$, $LEI$, $MMS$, $DMS$, $NES$, and $DES$ values needed for carrying out the mathematical computations.

The heuristic base is in charge of compiling the input data originated from ASPEN Plus, executing the problem-solving process of screening the identified failure modes and prioritizing them according to their involved risk, and developing the recommended availability structure diagram. Thus, it is provided with three different types of heuristics:

1. Heuristics for discerning the types of chemical process equipment involved in the ASPEN Plus output file,

2. Heuristics for screening the equipment failure modes through the computation of the Likelihood Coefficient $LC$, and,

3. Heuristics for determining the final Priority Index for each screened failure mode through the computation of the Likelihood, Local Effects, Product Effects, and Secondary Failures Indices.
Figure 4.1 System Architecture
In essence, the heuristics database is responsible for structuring the final system availability diagram through the firing of if-then statements constructed from drawn expertise, and the application of pertinent fuzzy reasoning algorithms.

The output generator consists of a series of procedures that create a data file named “report.out” with the final RCM analysis (see Section 4.4.3). Besides of being displayed by the system, this text file can be easily edited by any word processor, or exported to any application software that the user considers convenient.

4.4 Expert Analysis Procedure

The first task of the system is to identify the number and types of machines, as well as their corresponding positions in the process flowsheet generated by ASPEN Plus. Then it starts the solving-problem process by questioning the user about the operation conditions to which such machines are subjected. Through the application of the fuzzy logic reasoning discussed in Chapter 3, the heuristics base computes the Likelihood Coefficient for all failure modes involved in the analysis, selecting those which have Likelihood Coefficients higher than the pre-established threshold values. Once this screening process its completed, the system computes the Priority Index for each selected failure mode, and sorts them in descending order according to such indices. Finally, it opens a data file named “report.out” where the final RCM report is saved for further analysis of the user.

4.4.1 ASPEN Plus Interface

Figure 4.2 illustrates a typical report generated by ASPEN Plus. The developed expert system reads the From and To rows of that report, identifying distinct pieces of
equipment, and storing how they are arranged in the production process. That is, given a specific machine, it identifies nearby and downstream pieces of equipment.

In order for the system to be able to do that, the ASPEN Plus user has to employ the nomenclature depicted in Table 4.1 as embedded words in the names of his process machinery. For example, machines HEAT_A, HEAT_B, and HEAT_C contained in the report shown in Figure 4.2 will be considered as three distinct machines by the expert system, while it will only recognize a single distillation tower named DIST_TWA, although that name appears several times in the From and To rows.

Once the interface with ASPEN Plus is done, the system notifies the user the names of the machines that it identified from ASPEN Plus as shown in Figure 4.3. The system can handle up to 40 different pieces of equipment.

4.4.2 System Processing

The expert system interfaces with the user through a mouse-driven environment. Help screens are available to the user. A medium-sized window is opened at the upper-right corner of the monitor screen (see Figure 4.4) each time the user clicks on the “About” option of the Help menu.

A consultation starts when the user selects the 123 Lotus file or Excel file generated by ASPEN Plus where the flowsheet of the process to be analyzed has been stored (See Figure 4.5). Then, the program begins querying the user on the identified machines through the utilization of screens prompts. These query screens contain relevant questions on the operating conditions to which the scrutinized pieces of equipment are subjected. As seen in Figure 4.6, the analyst inputs the required
<table>
<thead>
<tr>
<th>Substream: MIXED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mole Flow KMOL/HR</td>
</tr>
<tr>
<td>H2O</td>
</tr>
<tr>
<td>NH3</td>
</tr>
<tr>
<td>CO2</td>
</tr>
<tr>
<td>H2S</td>
</tr>
<tr>
<td>NH4+</td>
</tr>
<tr>
<td>NH2COO-</td>
</tr>
<tr>
<td>HC02-</td>
</tr>
<tr>
<td>HS-</td>
</tr>
<tr>
<td>OH-</td>
</tr>
<tr>
<td>C03--</td>
</tr>
<tr>
<td>H30+</td>
</tr>
<tr>
<td>Total Flow KMOL/HR</td>
</tr>
<tr>
<td>Total Flow KG/HR</td>
</tr>
<tr>
<td>Temperature °C</td>
</tr>
<tr>
<td>Vapor Frac</td>
</tr>
<tr>
<td>Liquid Frac</td>
</tr>
<tr>
<td>Solid Frac</td>
</tr>
<tr>
<td>Enthalpy KCAL/KG</td>
</tr>
<tr>
<td>Entropy CAL/MOL-K</td>
</tr>
<tr>
<td>Entropy CAL/KG-K</td>
</tr>
<tr>
<td>Density KMOL/CUM</td>
</tr>
<tr>
<td>Density KG/CUM</td>
</tr>
<tr>
<td>Average MW</td>
</tr>
</tbody>
</table>

Figure 4.2 ASPEN Plus Sample Report
Table 4.1

System Nomenclature

<table>
<thead>
<tr>
<th>Equipment Type</th>
<th>Nomenclature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burner</td>
<td>BURNER</td>
</tr>
<tr>
<td>Centrifugal Blower</td>
<td>BLOWER</td>
</tr>
<tr>
<td>Centrifugal Pump</td>
<td>PUMP</td>
</tr>
<tr>
<td>Converter</td>
<td>CONVERTER</td>
</tr>
<tr>
<td>Distillation Tower</td>
<td>DIST_TW</td>
</tr>
<tr>
<td>Evaporator</td>
<td>EVAPORATOR</td>
</tr>
<tr>
<td>Heat Exchanger</td>
<td>HEAT</td>
</tr>
<tr>
<td>Multistage Compressor</td>
<td>COMPRESSOR</td>
</tr>
<tr>
<td>Pipeline</td>
<td>PIPE</td>
</tr>
<tr>
<td>Reactor</td>
<td>REACTOR</td>
</tr>
<tr>
<td>Waste Heat Boiler</td>
<td>BOILER</td>
</tr>
</tbody>
</table>
The expert system has identified the following pieces of equipment from your ASPEN Plus application:

- HEAT_A
- DIST_TWA
- HEAT_C
- HEAT_B

Figure 4.3 Equipment Identification Screen
The expert system has identified the pieces of equipment listed below from your ASPEN PLUS flowsheet report.

The RCM Expert System is now ready to start the inquiry regarding the operating conditions of these process machines.

Please, select the 'Start' option on the 'Analyze' menu to begin the consultation.

- BLOWER_1
- BLOWER_2
- EVAPORATOR
- PUMP
- BOILER
- REACTOR
- CONVERTER

Figure 4.4 Help Screen
information by typing a solicited numeric value in the corresponding prompt boxes. All query screens are provided with a bit-mapped drawing of the associated machine, as well as an explanation screen describing the equipment characteristics (see Figure 4.7). The heuristics base performs the needed fuzzy computations as the user inputs the data, and initiates the program routines that produce the final availability structure once all the Priority Indices for the selected failure modes have been computed.

**4.4.3 System Output**

When the heuristics base has screened and prioritized the most critical failure modes to be included in the final availability structure diagram, the system opens in the working directory a text file named *report.out*, where the system's analysis results are stored. This text file is displayed and can be printed at the end of the consultation through the system's conclusion module as shown in Figure 4.8.

A printout of the results generated during a typical system consultation is shown in Appendix F. The produced report consists of two major types of information. It first lists the names of those process machines that were considered by the expert system as not likely to develop any failure mode. It then depicts all the failure modes found to deserve attention, sorted in descending order according to their Priority Indices. For each failure mode shown, the software provides the user with relevant information on the failure mode's local and system effects, as well as a listing of suggested controls for its detection. It also reveals the failure modes corresponding Likelihood, Local Effects, Product Effects, and Secondary Failures Indices values, so that the analyst can take them into consideration while developing the process maintenance program.
Figure 4.5 Open File Window
Figure 4.6 Query Screen
Figure 4.7 Equipment Characteristics Information Screen
Project Name: SOUR.XLS

// CRITICAL FAILURE MODES //////////

Priority Index: 16 [ LL=2, LEL=2, PEL=2, SF=1 ]
DIST_TWA <> Plugged or Corroded Distributor.
Local Effects:
- Fluid contamination
- Reduced tower efficiency
- Poor liquid distribution
- Possible inappropriate column flooding

Figure 4.8 Conclusion Screen
4.5 Validation of the System

During recent years, several frameworks have been developed for the validation of knowledge based systems. Although validation researchers have struggled to discover the ultimate approach, there is not yet sufficient evidence to determine which approaches are more effective, or even which ones are reliable (4).

Systems similar to the one developed here are normally validated through the evaluation of test scenarios obtained from the available literature. The validity of such systems are determined by comparing the systems’ results with the actual results reported in the literature. However, the knowledge involved in this research is still unfamiliar to a large sector of the industry since it requires the understanding of precipitating factors and related interdependencies that are fuzzy in nature and intrinsically complex.

Therefore, the validation process employed in this project consisted of using the same experts from whom the knowledge was gathered to evaluate the performance of the system. As stated by Ayel and Laurent (1991), there are three advantages of using this approach:

1. Since the expert has been a part of the project, there is no major discrepancies between his expertise and the knowledge contained in the knowledge base.

2. Since the expert knows the kind of problems that falls within the knowledge boundaries of the system, he can select the appropriate scenarios to be used in the validation process.

3. The expert is accessible.

Hence, the qualitative validation of the constructed RCM expert system was carried out through the performance of a face validation conducted by the domain
experts, followed by a predictive validation. The rest of this chapter is devoted to the explanation of these validation techniques.

4.5.1 Face Validation

During a face validation, the domain expert reviews the developed system, and comments on its performance. For a prototype system, like the one constructed during this study, a face validation is appropriate to determine whether the system satisfies all functional specifications, as well as to detect any possible flaws of the system.

The RCM expert system was presented to the domain experts headed by Mr. Marco Araya, a current researcher and doctoral candidate in chemical engineering at the University of Alabama who has more than three years of experience as a process engineer for BASF, for their critique. Fictional cases were executed to demonstrate the system's performance as an analytical tool.

This validation process consisted of two major parts, the development of individual test cases for each of the eleven pieces of equipment considered by the system, and the development of test cases with process flowsheets comprising at least three different industrial machines. Regarding the individual test cases, ten to fifteen distinct scenarios were created for each machine type. Several working conditions were simulated, and the generated RCM analysis reports were carefully examined by the experts. The process test cases involved the construction of fictional scenarios where three to six machines were linked together. The main purpose of such test cases was to assess the performance of the expert system when estimating secondary failure effects.
Out of the ten processes discussed in Section 3.3.1, only the sulfuric acid and nitric acid processes could be fully evaluated by the expert system during the validation phase. The other eight chemical processes comprise equipment not included in the knowledge base of the system. Nevertheless, the following equipment arrangements were used during the validation of the system (the machines are listed in downstream order):

- Burner, Waste Heat Boiler, Converter, Blower, and Heat Exchanger
- Compressor, Distillation Tower, Heat Exchanger, and Pump
- Reactor, Pipe, Pump, and Evaporator
- Blower, Pipe, Reactor, Distillation Tower, and Pump
- Centrifugal Compressor, Burner, Blower, and Waste Heat Boiler
- Converter, Pump, Burner, Blower, Pipe, and Reactor

In general, the experts gave favorable feedback (see Appendix G). The system’s query methodology was rated by the experts as effective in capturing the most relevant factors affecting the normal functioning of the process machinery. Moreover, the conclusions reached at the end of most of the consultations were regarded as satisfactory.

Nevertheless, the experts expressed their concerns with the way in which factors such as the atomizing air rate for the burner, catalyst pH for the converter, liquid feed rate for the distillation tower, rotor speed for the reactor, and water pH for the waste heat boiler were classified and weighted by the system. Moreover, some employed technical terms such as *distillate substance* (instead of leaving liquid) and *fed liquid* (instead of feeding liquid) for the distillation tower query were catalogued as “erroneous” by the
experts. They also objected the selection of the CO₂ environment as the only corrosive environment considered by the system for determining gas corrosivity.

In response to their criticisms, the identified precipitating factors were reclassified and their corresponding weights changed according to the experts' expectations, the technical terms used in the different modules of the system reviewed and modified in accordance to the technical language used in the chemistry field, and the H₂SO₄ corrosive environment incorporated into the system's analytical procedure.

Finally, the prototype system was shown to Mr. Ricardo Mora, a maintenance engineer at DSM Shessield Plastics, located in Pittsfield, Massachusetts. Mr. Mora, who did not take part in the knowledge engineering phase of this research, utilized the expert system to individually analyze the operating conditions of blowers, compressors, pumps, and heat exchangers normally employed in the plant. His comments of the system's responses were also favorable. He indicated that the failure modes revealed by the expert system were common, and did precipitate with a relatively high frequency in the plant.
CHAPTER 5
CONCLUSIONS AND FUTURE RESEARCH

5.1 Comments on This Research

This work has focused on the development of a innovative new framework for the implementation of reliability centered maintenance in industrial settings. The main means used for reaching such a goal was the creation of a computer expert system that successfully embodied both relevant maintenance and equipment expertise, and efficient approximate reasoning techniques. Thus, the final product of this study was a versatile knowledge-based system for the application of RCM in the chemical industry. Although the chemical process industry was selected as the application domain for this research, the developed RCM framework postulated here was designed to be implemented in all the maintenance activity spectrum regardless of the type of industry. Therefore, it is encouraged to use this RCM methodology in other manufacturing areas such as the automotive, metallurgic, power, and aviation industries among others.

This work represents a pioneer effort in automating the implementation of RCM via an intelligent computer system. This study has also incorporated a technique that has proven successful in other areas of knowledge, fuzzy reasoning, in the evaluation and assessment of equipment failure modes. Finally, an alternative to the traditional RCM decision tree for prioritizing failure modes was presented through the development of the Priority Index, which not only takes into account the relevancy of the failure modes local and product effects, but also their likelihood of occurring as well as associated negative consequences on adjacent machinery.
5.2 Key Contributions

The completed research substantially contributes to the area of equipment maintenance management. First, it provided industrial practitioners with a versatile tool for estimating possible machine failure occurrences. This tool enables them to better comprehend the complexity of failure mode interdependencies and devise appropriate reliability maintenance strategies. Second, the study produced an innovative new framework for Reliability Centered Maintenance, which can be characterized by the flexibility typical of computer based knowledge systems. Finally, the utilization of approximate reasoning in both the screening and prioritization of distinct equipment failure modes represents an extension of the available knowledge in reliability management. It brings a better understanding of the mechanics involved in equipment reliability and maintainability through a new technique for failure mode analysis and functional interdependency assessment.

With respect to the chemical process industry, a new chapter in the analysis and evaluation of failure mode precipitating factors was written through the quantification and fuzzification of critical, important, and related factors for each one of the eighty failure modes under scrutiny. However, the most important benefit resulting from this research is the eventual implementation of prototype expert systems built according to the methodology here developed, which will lead to the propagation of equipment maintenance expertise to industrial settings. Process engineers will be able to reduce production losses by properly detecting and addressing potential failures of key pieces of equipment early in the production process designing stages, or as a complementary
reliability centered maintenance tool to their conventional maintenance management strategies when historical records of machinery malfunctions are available.

5.3 Recommendations for Future Research

This work can be extended through the implementation of any or all of the following recommendations:

- The developed expert system could be provided with a learning capability to improve the accuracy of its final output. When discrepancies exist, the user should be allowed to indicate what specific failure modes he was expecting to see in the final availability structure diagram. Then, the system’s learning engine should alter the corresponding precipitating factors weights and magnitude limits in such a way that the output of the failure mode screening phase could meet the expert’s expectations.

- More research is needed to develop a more realistic precipitating factor fuzzification process. During this study, linear fuzzification was assumed since, according to the available literature, it is a widely used practice that has shown to yield acceptable results. Nevertheless, there is no guarantee that the effect of a particular failure mode linearly increases as its critical limits are reached. An exponential, logarithm, or normal distribution, just to give examples, may describe more accurately the behavior of this factor effect-limit relationship.

- While determining the different failure mode Priority Indices, the dimensions of the production process should be taken into account in the analysis. In this
study, only adjacent pieces of equipment were considered when assessing secondary failure effects. However, this should be a function of the distances between the machine presenting the failure mode, and all other process equipment.

- Regarding the assignment of threshold values for failure mode screening, such values could be defined as varying terms associated to the factors precipitating the failure modes. Hence, instead of a fixed threshold value as the one assumed in this research, a mathematical model or function should be defined for determining such failure mode threshold values according to the number of precipitating factors involved, and their corresponding weights and magnitude limits.

- A back propagation neural network could be embedded into the system to assist the experts in the classification of precipitating factors, and in the assignment of their associated weights, so that more accurate knowledge can be added to the system. Three types of precipitating factors were defined in this study: critical, important, and related factors; however, for other applications, such a classification may be inappropriate. Thus, if machine failure records exist where operational conditions have been registered, a neural network model could be employed to help in the clustering of identified precipitating factors, and in the assessment of the magnitude which such factors influence the precipitation of the distinct equipment failure modes.
Finally, crisp magnitude limits were adopted here for each one of the identified failure mode precipitating factors. However, there may be some cases where fuzzy rather than crisp limits might be more appropriate and realistic. When fuzzy limits are assumed for a particular precipitating factor, its resulting trapezoidal number will differ from the ones defined in this research since there will be not any abrupt rise or fall of the factor-effect function once the limits are encountered. Instead, a smooth curve should characterize the fuzzified function.
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70. Molloy, E., 1941, Pipes and Valves (Brooklyn: Chemical Publishing Company, Inc.).


APPENDIX A
IDENTIFIED PROCESS EQUIPMENT AND THEIR FAILURE MODES

The following pieces of equipment and their corresponding failure modes were obtained from the ten chemical processes discussed in Section 3.3.1. The literature sources used in this analysis are listed in the references [9, 16, 17, 30, 45, 53, 55, 63, 64, 65, 66, 78, 81, 86, 89, 90, 98].

ACID TANK
1. cracked or damaged shell 2. clogged roof drain 3. defective porcelain plug valve 4. corroded tank shell 5. damaged outside painting 6. damaged discharge nozzle seal 7. corroded tank vent 8. damaged roof support 9. leaking drain trap 10. stuck safety valve

AIR FILTER
1. corroded screens 2. deformed screens 3. stuck screen curtains gears 4. clogged screens 5. material deposits inside motor 6. empty rinsing oil cleaning receptacle 7. broken curtain travel band 8. defective sludge scraper

BLOWER
1. obstructed inlet and outlet ducts 2. cracked inlet box 3. misalign wheel bearings 4. cracked wheel 5. damaged shaft seals 6. expanded shaft 7. worn wheel blades 8. misalign couplings and inlet bells 9. worn scroll and housing liners

BRINE PURIFIER
1. damaged heating coils 2. faulty in-flow valves 3. clogged tank outlets 4. worn stirrer bearings 5. non-lubricated drive bearings and gears 7. damaged nozzle seals

BUBBLE-CAP TOWER
1. leaking liquid draw-off nozzle 2. clogged liquid draw-off outlet 3. corroded bubble
caps 4. bent trusses 5. wrapped caps cracked trays 6. deformed cap riser 7. obstructed vapor outlet 8. defective vapor flow valve

**BURNER**

**CALCINER**
1. deformed lifting bars 2. stuck scraper chain 3. leaking gas seals 4. dirty burner tips 5. worn motor drive and bearings 6. clogged discharge chute 7. defective water sprays 8. cracked pan burners

**CARBONATING TOWER**
1. blinded plate apertures 2. cracked cooling coils 3. corroded or plugged inlet/outlet nozzles 3. deformed plate convex caps 4. plugged baffles and cooling pipes 5. obstructed magma outlet 6. damaged CO₂ inlet nozzle

**CO₂ ABSORBER**
1. deformed rings 2. unevenly spaced support grid bars 3. unleveled acid distributor 4. crushed intermediate packing layers 5. deformed vapor distributor hats 6. unattached hold down grid 7. blown off chimney tray pan hats 8. defective liquid draw-off nozzle

**CO₂ STRIPPER**
1. deformed rings 2. unevenly spaced support grid bars 3. unleveled acid distributor 4. crushed intermediate packing layers 5. deformed vapor distributor hats 6. unattached hold down grid 7. blown off chimney tray pan hats 8. defective liquid draw-off nozzle

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COMPRESSOR
1. deformed thrust bearings 2. plugged stationary elements 3. eroded impeller exit tips 4. damaged shaft and inter-stage seals 5. misalign shaft

CONDENSER
1. broken expansion joints 2. cracked tubes 3. deformed impingement plate 4. loose bell head 5. torn loose tubes 6. dirty tubes 7. corroded exchanger surfaces

CONVERTER
1. damaged supporting grids 2. corroded or cracked supporting flanges 3. plugged vessel walls and ducts 4. fouled heat exchanger tubes

CRUSHER
1. bent eccentric shaft 2. worn jaws 3. clogged discharge opening 4. non-lubricated shaft bearings 5. damaged belts 6. loose stationary jaw

CRYSTALLIZER
1. leaking storage pan 2. defective heating device 3. defective screw drive shaft 4. corroded piping 5. defective gates

CYLINDRICAL COOLER
1. clogged discharge duct 2. non-lubricated shaft bearings 3. worn wheel blades 4. worn toothed band 5. broken rotation band 6. dirty motor 7. misalign shaft bearings

DEBUTANIZER
1. deformed rings 2. unevenly spaced support grid bars 3. unleveled acid distributor 4. crushed intermediate packing layers 5. deformed vapor distributor hats 6. unattached hold down grid 7. blown off chimney tray pan hats 8. defective liquid draw-off nozzle
DEETHANIZER
1. deformed rings 2. unevenly spaced support grid bars 3. unlevelled acid distributor 4. crushed intermediate packing layers 5. deformed vapor distributor hats 6. unattached hold down grid 7. blown off chimney tray pan hats 8. defective liquid draw-off nozzle

DEMETHANIZER
1. deformed rings 2. unevenly spaced support grid bars 3. unlevelled acid distributor 4. crushed intermediate packing layers 5. deformed vapor distributor hats 6. unattached hold down grid 7. blown off chimney tray pan hats 8. defective liquid draw-off nozzle

DEPROPNANIZER
1. deformed rings 2. unevenly spaced support grid bars 3. unlevelled acid distributor 4. crushed intermediate packing layers 5. deformed vapor distributor hats 6. unattached hold down grid 7. blown off chimney tray pan hats 8. defective liquid draw-off nozzle

DIAPHRAGM CELL
1. worn titanium anodes 2. plugged diaphragm pores 3. dirty diaphragm surface 4. corroded or defective lead casting 5. clogged overflow pipe

DIGESTOR
1. worn stirrer bearings 2. non-lubricated drive bearings and gears 3. corroded tank walls 4. damaged discharge nozzle seal 5. defective heating coils 6. corroded or plugged inlets and outlets

DISTILLATION TOWER
1. deformed or broken rings 2. unlevelled liquid distributor 3. plugged or corroded distributor 4. fouled column packing or internals

DRIER
1. clogged discharge duct 2. non-lubricated shaft bearings 3. worn wheel blades 5. worn toothed band 6. broken rotation band 7. dirty motor 8. misalign shaft bearings
DRUM FILTER
1. blinded cloth 2. faulty automatic control valve 3. worn rotating and stationary surfaces 4. damaged stub spring 5. clogged internal compartment pipes 6. deformed or worn doctor blade 7. defective water sprays 8. worn drum bearings and shaft 9. clogged discharge outlet

DRYING TOWER
1. deformed rings 2. unevenly spaced support grid bars 3. unleveled acid distributor 4. crushed intermediate packing layers 5. deformed vapor distributor hats 6. unattached hold down grid 7. blown off chimney tray pan hats 8. defective liquid draw-off nozzle

ECONOMIZER
1. broken expansion joints 2. cracked tubes 3. deformed impingement plate 4. loose bell head 5. torn loose tubes 6. dirty tubes 7. corroded exchanger surfaces

EVAPORATOR

FRACTIONATOR
1. deformed rings 2. unevenly spaced support grid bars 3. unleveled acid distributor 4. crushed intermediate packing layers 5. deformed vapor distributor hats 6. unattached hold down grid 7. blown off chimney tray pan hats 8. defective liquid draw-off nozzle

FURNACE
1. leaking convective gas section 2. dirty or corroded tube interior 3. bulged tubes 4. thermally cracked tubes 5. damaged diffusion baffle tile system 6. cracked side-wall banks 7. damaged fuel-flow control valve
GAS MIXER

GAS-H₂O SEPARATOR
1. faulty gas-flow control valve  2. cracked tube sheet  3. dirty fiber packing  4. damaged separator seals  5. broken tubes  6. bad-mounted tubes  7. perforated packing or vanes

H₂O-COoled COOLER
1. clogged discharge duct  2. non-lubricated shaft bearings  3. defective water sprays  4. worn toothed band  5. broken rotation band  6. dirty motor  7. misalign shaft bearings  8. cracked water pipe

HEAT EXCHANGER
1. broken tube support baffles  2. cracked tubes  3. deformed impingement plate  4. fouled tubes  5. corroded exchanger and kettle surfaces

HEATER

HUMIDIFIER
1. dirty damper  2. corroded fan blades  3. plugged spray chambers  4. dirty diffuser  5. non-lubricated motor bearings  6. torn seals

HYDROGENATOR
1. contaminated catalyst  2. cracked vessel shell  3. faulty hydrogen flow control valve  4. faulty internal heat exchanger  5. faulty reactant gas control valve
KILN
1. leaking kiln roof  2. clogged upright duct  3. dirty burner tips  4. clogged coal feeder  5. clogged air flow nozzles  6. cracked pan burners  7. dirty fire and ducts zones  8. stuck hoist

METHANATOR
1. contaminated catalyst  2. cracked vessel shell  3. faulty hydrogen flow control valve  4. faulty internal heat exchanger  5. faulty reactant gas control valve

OXIDATION CHAMBER
1. deformed rings  2. unevenly spaced support grid bars  3. unlevelled acid distributor  4. crushed intermediate packing layers  5. deformed vapor distributor hats  6. unattached hold down grid  7. blown off chimney tray pan hats  8. defective liquid draw-off nozzle

PADDLE MIXER
1. worn agitator bearings  2. non- lubricated drive bearings and gears  3. corroded tank walls  4. damaged discharge nozzle seals

PIPE
1. leaking fittings or joints  2. cracked pipe wall  3. plugged inner section  4. bent pipe  5. corroded or eroded inner wall

PRILLING TOWER
1. clogged spray nozzles  2. faulty liquid inlets  3. faulty liquid distributor  4. defective hot air valve

PRILLS TANK
1. cracked floor  2. damaged shell  3. splintered tank material  4. damaged drain outlet  5. broken roof support  6. clogged vent
PUMP
1. damaged mechanical seals in stuffing box 2. worn impeller 3. faulty thrust bearings
4. deformed shaft 5. leaking casing 6. faulty shaft couplings 7. faulty impeller wear ring

QUENCH TOWER
1. deformed rings 2. unevenly spaced support grid bars 3. unleveled acid distributor 4.
crushed intermediate packing layers 5. deformed vapor distributor hats 6. unattached
hold down grid 7. blown off chimney tray pan hats 8. defective liquid draw-off nozzle

REACTOR
1. worn or faulty stirrer couplings 2. non-lubricated drive bearings and gears 3. damaged
discharge nozzle seals 4. defective heating coils

REBOILER
1. corroded internal elements 2. leaking tower bottom tray 3. damaged seal pan 4.
damaged draw-off pan 5. partially plugged reboiler 6. restricted reboiler feed line 7.
submerged reboiler vapor return nozzle 8. leaking housing tower 9. clogged reboiler
outlet line

RECIPROCATING COMPRESSOR
1. worn pistons, liners, packing and rods 2. dirty packing caps 3. broken valves 4.
damaged cylinder seat 5. incorrectly spaced piston 6. loose piston nut 7. misalign
cylinder 8. faulty piston rings 9. burned or leaky valves 10. worn valve operating gear

REFORMER
1. defective steam inlet valves 2. dirty or corroded tube interior 3. bulged tubes 4.
thermally cracked tubes 5. contaminated catalyst 6. cracked cylinder shell 7. defective
reactant gas flow valve 8. deformed catalyst packing
SATURATOR
1. blinded efflux holes  2. faulty or clogged overflow device  3. cracked cooling coil  4. corroded or plugged inlet/outlet nozzles  5. deformed bottom grill

SETTLING TANK
1. leaking outlet seals  2. leaking bottom outlet seal  3. corroded tank shell

SLAKER
1. clogged discharge duct  2. non-lubricated shaft bearings  3. defective or clogged water pipe nozzle  4. worn toothed band  5. broken rotation band  6. dirty motor  7. misalign shaft bearings  8. corroded drum walls

STIRRED MILL
1. corroded grinder body  2. worn grinding vanes  3. plugged armature rotating base  4. defective armature base seals  5. worn armature bearings  6. non-lubricated drive bearings and gears

TILTING PAN FILTER
1. blinded cloth  2. clogged or corroded distributor tubes  3. defective wash sprays  4. worn filter medium  5. stuck or corroded pan rotating axis  6. faulty automatic vacuum valve  7. worn roller bearings or gears  8. defective pan inverting mechanism

TREATMENT TANK
1. worn stirrer bearings  2. non-lubricated drive bearings and gears  3. corroded tank walls  4. damaged discharge nozzle seal  5. defective heating coils  6. corroded or plugged inlets and outlets

TROMMEL
1. faulty speed controller  2. blinded screens  3. worn spur-girt gear  4. obstructed structural members  5. deflected central shaft
**TUBULAR COOLER**
1. broken expansion joints 2. cracked tubes 3. damaged bell head seals 4. plugged tubes 5. torn loose tubes 6. corroded surfaces

**TURBINE**
1. worn flexible coupling teeth 2. non-lubricated bearings 3. sticky pipe or pedestal 4. misalign shaft 5. sticky valve stems 6. leaking valves 7. damaged sleeves 8. leaking glands

**TURBO EXPANDER**

**VESSEL**
1. cracked vessel shell 2. faulty valves 3. corroded shell 4. damaged drain outlet 5. defective pressure controller

**WASTE HEAT BOILER**
1. broken expansion joints 2. fouled tubes 3. deformed demister mesh pad 4. cracked boiler drum shell
APPENDIX B

FAILURE MODES EFFECTS AND SUGGESTED CONTROLS

The information presented in this appendix was obtained from relevant equipment maintenance literature shown in the references.

BURNER Ref. [9, 21, 23, 24, 25, 53, 63, 86, 108]

A. Obstructed Inlet or Outlet Ducts of Blower.
   Local Effects:
   - Diminished gas flow delivered by blower
   - Possible overloading of blower motor
   - May precipitate blower seals damage
   System Effects:
   - Electrical power supply to other equipment may be affected if blower motor overloads
   - Explosion hazard
   - A considerable amount of atmospheric pollutants may be released by burner
   Suggested Controls:
   - Visual inspection
   - Protective screens test

B. Cracked Inlet Box of Blower.
   Local Effects:
   - Flow pressure loss in blower
   - Overloading of the fan motor
   - Gas/air leakage
   - Eventual loss of air flow
   System Effects:
   - Electrical power supply to other equipment may be affected if blower motor overloads
   - Contamination hazard
   - Possible corrosive effect on nearby equipment
   - Explosion hazard
   - Increase in atmospheric pollutants
   Suggested Controls:
   - Gas detector
   - Visual inspection
   - Dye penetrant inspection
C. Misaligned Wheel Bearings of Blower.
Local Effects:
- Fan motor overloaded
- Possible bending of blower's shaft
- Extreme blower vibration and noise
- Blowing power loss
- Eventual decrease in air flow to combustion chamber
- Burner efficiency reduced

System Effects:
- Electrical power supply to other equipment may be affected if blower motor overloads
- Nearby equipment may be atrophied due to transmitted vibration

Suggested Control:
- Mechanical running test
- Visual inspection
- Vibration analysis
- Rotor stability test

D. Cracked Wheel of Blower.
Local Effects:
- Total loss of blower operation
- Impeller may fall off
- Possible severe damage to fan motor
- Eventually, burner operation must be shut down

System Effects:
- Electrical power supply to other equipment may be affected if blower motor overloads
- Explosion Hazard

Suggested Controls:
- Dye penetrant inspection
- Fluorescent (Zyglo) inspection

E. Damaged Shaft Seals of Blower.
Local Effects:
- Gas/air leakage around shaft
- Loss of blower pressure and efficiency
- Possible corrosion of other elements in blower
- Low combustion efficiency

System Effects
- Electrical power supply to other equipment may be affected if blower motor overloads
- Contamination hazard
- Possible corrosive effect on nearby equipment
- Increase in atmospheric pollutants
- Explosion hazard

Suggested Controls:
- Static gas test
- Visual inspection
- Temperature detectors (thermocouples & electrical resistance detectors)

F. Expanded Shaft of Blower.

Local Effects:
- Extreme blower vibration upon startup
- Eventual failure of blower bearings
- Possible blower seals damage
- Reduction in air flow to combustion chamber

System Effects:
- Temperature in the area may get out of control and nearby equipment nozzles and pipes can be damaged
- Nearby equipment may be affected by transmitted vibration
- Explosion hazard
- Increase in air pollutants originated from combustion

Suggested Controls:
- Mechanical running test
- Vibration analysis
- Temperature detectors (thermocouples & electrical resistance detectors)

G. Worn Wheel Blades of Blower.

Local Effects:
- Diminished delivered air/gas flow
- Possible unbalance of blower shaft
- Combustion efficiency reduced

System Effects:
- Increase in atmospheric pollutants originated from combustion

Suggested Controls:
- Visual inspection
- Rotor stability test

H. Misaligned Couplings Inlet Bells of Blower.

Local Effects:
- Overheating of blower bearings and motor
- Bearing failure
- Increase of bearing dust seals wear
- Air flow to combustion chamber possibly reduced
- Combustion efficiency affected

System Effects:
- Electrical power supply to other equipment may be affected if blower motor overloads
Suggested Controls:
- Temperature detectors (thermocouples & electrical resistance detectors)
- Mechanical test
- Visual inspection

I. Worn Scroll and Housing Liners of Blower.
   Local Effects:
   - Damaged blower liners can break free
   - Eventual damage to blower wheel
   - If wheel breaks, air flow to combustion chamber will cease
   - Burner operation eventually must be shut down
   System Effects:
   - Explosion hazard
   - Liners debris may be blown away and cause major problems to connected equipment such as compressors, converters, heaters, etc.
   - Nearby equipment may get affected by transmitted vibration
   Suggested Controls:
   - Visual inspection
   - Magnetic particle inspection
   - Mechanical running test

J. Damaged Mechanical Seals in Stuffing Box of Pump.
   Local Effects:
   - Pump’s capacity severely reduced
   - Increase in pump vibration
   - Combustion greatly affected
   - Burner efficiency greatly reduced
   System Effects:
   - Contamination hazard
   - Transmitted vibration may damage close machinery
   - Corrosion problems may prevail in adjacent areas
   Suggested Controls:
   - Hydrostatic pressure test
   - Visual inspection

K. Worn Impeller of Pump.
   Local Effects:
   - Pump’s capacity severely reduced
   - Increase in pump vibration
   - Reduction in suction power
   - Combustion reduced
   - Burner gas quality greatly affected
System Effects:
- Upstream ducts may get clogged
- Transmitted vibration may damage attached pipes or equipment
- Associated compressors and turbines may overload

Suggested Controls:
- Hydrostatic pressure test
- Flow analysis
- Visual inspection

L. Faulty Thrust Bearings of Pump.
Local Effects:
- Excessive pump vibration
- Pump motor may overload and run hot
- Possible shaft/gear misalignment
- Increase in shaft radial movement
- Eventual pump shut down
- Burner operation may have to be stopped

System Effects:
- Destructive equipment vibration
- If motor overloads, nearby equipment may experience electrical problems
- If pump ceases working, related equipment detriment should be expected

Suggested Controls:
- Pressure pulsation (piezoelectric pressure) test
- Visual inspection
- Vibration analysis
- Bearing temperature control

M. Deformed Shaft of Pump.
Local Effects:
- Pumping efficiency greatly reduced
- Excessive pump vibration
- Increase in shaft radial movement
- Possible pump bearings damage
- Possible pump seals damage
- Eventual pump couplings failure
- Burner gas quality greatly affected
- Burner may have to be shut down

System Effects:
- Destructive equipment vibration
- Possible clogging of attached pipes
- Fluid leakage around shaft may increase, which could lead to contamination problems

Suggested Controls:
- Visual inspection
- Tensile stress analysis
- Pressure pulsation (piezoelectric pressure) test
- Vibration analysis

N. Leaking Casing of Pump.
Local Effects:
- Reduced pumping rate
- Possible corrosion effects on pump elements
- Combustion efficiency reduced
- Burner gas quality greatly affected

System Effects:
- Contamination hazard
- Explosion hazard
- Corrosion problems in nearby machinery

Suggested Controls:
- Visual inspection
- Hydrostatic pressure test
- Flow analysis

O. Faulty Shaft Couplings of Pump.
Local Effects:
- Pump shaft misalignment
- Atrophied shaft movement
- Loss of pumping efficiency
- Increase in pump noise and vibration
- Possible pump seals damage
- Eventually, pump total shut down
- Burner gas quality greatly reduced
- Eventually, burner may have to be shut down

System Effects:
- Destructive equipment vibration
- If pump ceases working, related equipment detriment should be expected
- Possible clogging of attached pipes
- Fluid leakage around shaft may increase, which could lead to contamination problems

Suggested Controls:
- Visual inspection
- Vibration analysis
- Pressure pulsation (piezoelectric pressure) test
P. Faulty Impeller Wear Ring of Pump.

Local Effects:
- Internal liquid leakage from the pump discharge back the pump suction
- Eminent pump impeller wear
- Potential corrosion effect on pump's internals
- Pump's capacity greatly reduced
- Combustion efficiency greatly reduced

System Effects:
- Contamination hazard
- Possible clogging of attached pipes
- Downstream equipment may be detrimentally affected

Suggested Controls:
- Visual inspection
- Flow analysis
- Venturi analysis
- Hydrostatic pressure test

Q. Plugged Spray Nozzle in Combustion Chamber.

Local Effects:
- Poor air flow stream
- Increase in atmospheric pollutants originated from the combustion
- Burner capacity greatly reduced

System Effects:
- Explosion hazard

Suggested Effects:
- Pollutant detector
- Visual inspection
- Venturi analysis

R. Carbonaceous Matter Formation in Combustion Chamber.

Local Effects:
- Combustion interference
- Vaporization unsteady

System Effects:
- No major effects on downstream equipment expected

Suggested Controls:
- Visual inspection
CENTRIFUGAL BLOWER  Ref. [10, 16, 77, 53, 64, 78]

A. Obstructed Inlet or Outlet Ducts.
   Local Effects:
   - Diminished gas/air flow delivered by blower
   - Possible overloading of blower motor
   - May precipitate seals damage

   System Effects:
   - If blower used for cooling, system components or product temperature may get out of control
   - Electrical power supply to other equipment may be affected if blower motor overloads

   Suggested Controls:
   - Visual inspection
   - Protective screens test

B. Cracked Inlet Box.
   Local Effects:
   - Flow pressure loss
   - Overloading of the fan motor
   - Gas/air leakage
   - Eventual loss of equipment's function

   System Effects:
   - If blower used for cooling, system components or product temperature will get out of control
   - Electrical power supply to other equipment may be affected if blower motor overloads
   - If handling gas, contamination hazard
   - Possible corrosive effect on nearby equipment

   Suggested Controls:
   - Gas detector
   - Visual inspection
   - Dye penetrant inspection

C. Misaligned Wheel Bearings.
   Local Effects:
   - Motor overloaded
   - Possible bending of shaft
   - Extreme equipment vibration and noise
   - Blowing power loss

   System Effects:
   - If blower used for cooling, system components or product temperature may get out of control
   - Electrical power supply to other equipment may be affected if blower motor overloads

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- Nearby equipment may be atrophied due to transmitted vibration

Suggested Control:
- Mechanical running test
- Visual inspection
- Vibration analysis
- Rotor stability test

D. Cracked Wheel.
Local Effects:
- Total loss of equipment operation
- Impeller may fall off
- Possible severe damage to fan motor

System Effects:
- If blower used for cooling, system components or product temperature will get out of control
- Electrical power supply to other equipment may be affected if blower motor overloads

Suggested Controls:
- Dye penetrant inspection
- Fluorescent (Zyglo) inspection

E. Damaged Shaft Seals.
Local Effects:
- Gas/air leakage around shaft
- Loss of blower pressure and efficiency
- Possible corrosion of other elements

System Effects:
- If blower used for cooling, system components or product temperature will get out of control
- Electrical power supply to other equipment may be affected if blower motor overloads
- If handling gas, contamination hazard
- Possible corrosive effect on nearby equipment

Suggested Controls:
- Static gas test
- Visual inspection
- Temperature detectors (thermocouples & electrical resistance detectors)

F. Expanded Shaft.
Local Effects:
- Extreme vibration upon startup
- Eventual failure of bearings
- Possible seals damage
System Effects:
- If blower used for cooling, system components or product temperature may get out of control
- Nearby equipment may be affected by transmitted vibration
Suggested Controls:
- Mechanical running test
- Vibration analysis
- Temperature detectors (thermocouples & electrical resistance detectors)

G. Worn Wheel Blades.
Local Effects:
- Diminished delivered air/gas flow
- Possible unbalance of shaft
System Effects:
- If blower used for cooling, system components or product temperature may get out of control
Suggested Controls:
- Visual inspection
- Rotor stability test

H. Misaligned Couplings Inlet Bells.
Local Effects:
- Overheating of bearings and motor
- Bearing failure
- Increase of bearing dust seals wear
System Effects:
- Electrical power supply to other equipment may be affected if blower motor overloads
Suggested Controls:
- Temperature detectors (thermocouples & electrical resistance detectors)
- Mechanical test
- Visual inspection

I. Worn Scroll and Housing Liners.
Local Effects:
- Damaged liners can break free
- Eventual damage to wheel
- No immediate loss of efficiency expected
System Effects:
- Liners debris may be blown away and cause major problems to connected equipment such as compressors, converters, heaters, etc.
- Nearby equipment may get affected by transmitted vibration

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Suggested Controls:
- Visual inspection
- Magnetic particle inspection
- Mechanical running test

CENTRIFUGAL PUMP Ref. [8, 15, 41, 42, 74, 86, 89, 108]

A. Damaged Mechanical Seals in Stuffing Box.
   Local Effects:
   - Pump's capacity severely reduced
   - Increase in equipment vibration
   - Possible fluid leakage
   System Effects:
   - If pumping fluid is toxic, contamination hazard
   - Transmitted vibration may damage close machinery
   - Corrosion problems may prevail in adjacent areas
Suggested Controls:
- Hydrostatic pressure test
- Visual inspection

B. Worn Impeller.
   Local Effects:
   - Pump's capacity severely reduced
   - Increase in machine vibration
   - Reduction in suction power
   System Effects:
   - Upstream ducts may get clogged
   - Transmitted vibration may damage attached pipes or equipment
   - Associated compressors and turbines may overload
Suggested Controls:
- Hydrostatic pressure test
- Flow analysis
- Visual inspection

C. Faulty Thrust Bearings.
   Local Effects:
   - Excessive pump vibration
   - Motor may overload and run hot
   - Possible shaft/gear misalignment
   - Increase in shaft radial movement
   - Eventual pump shut down
   System Effects:
   - Destructive equipment vibration
   - If motor overloads, nearby equipment may
experience electrical problems
- If pump ceases working, related equipment detriment should be expected

Suggested Controls:
- Pressure pulsation (piezoelectric pressure) test
- Visual inspection
- Vibration analysis
- Bearing temperature control

D. Deformed Shaft.
Local Effects:
- Pumping efficiency greatly reduced
- Excessive pump vibration
- Increase in shaft radial movement
- Possible bearings damage
- Possible seals damage
- Eventual couplings failure

System Effects:
- Destructive equipment vibration
- Possible clogging of attached pipes
- Fluid leakage around shaft may increase, which could lead to contamination problems

Suggested Controls:
- Visual inspection
- Tensile stress analysis
- Pressure pulsation (piezoelectric pressure) test
- Vibration analysis

E. Leaking Casing.
Local Effects:
- Reduced pumping rate
- Possible corrosion effects on pump's components and attachments

System Effects:
- If pumping fluid is toxic, contamination hazard

Suggested Controls:
- Visual inspection
- Hydrostatic pressure test
- Flow analysis

F. Faulty Shaft Couplings.
Local Effects:
- Shaft misalignment
- Atrophied shaft movement
- Loss of pumping efficiency
- Increase in pump noise and vibration
- Possible seals damage
- Eventually, pump total shut down

System Effects:
- Destructive equipment vibration
- If pump ceases working, related equipment detriment should be expected
- Possible clogging of attached pipes
- Fluid leakage around shaft may increase, which could lead to contamination problems

Suggested Controls:
- Visual inspection
- Vibration analysis
- Pressure pulsation (piezoelectric pressure) test

G. Faulty Impeller Wear Ring.

Local Effects:
- Internal liquid leakage from the pump discharge back the pump suction
- Eminent impeller wear
- Potential corrosion effect on pump's internals
- Pump's capacity greatly reduced

System Effects:
- Contamination hazard
- Possible clogging of attached pipes
- Downstream equipment may be detrimentally affected

Suggested Controls:
- Visual inspection
- Flow analysis
- Venturi analysis
- Hydrostatic pressure test

CONVERTER Ref. [21, 23, 45, 51, 63, 64]

A. Damaged Supporting Grids.

Local Effects:
- Potential catalyst loss
- Catalyst bed disarrangement
- Eventual loss of reaction efficiency

System Effects:
- Batch of material in process may have to be wasted
- Catalyst debris may obstruct attached ducts

Suggested Controls:
- Visual inspection
B. Corroded or Cracked Supporting Flanges.
Local Effects:
- Diminished conversion efficiency
- Possible catalyst contamination
- Weakening of converter structure
System Effects:
- Besides the loss in the quality of the reaction no major effects on nearby equipment should be expected
Suggested Controls:
- Visual inspection
- Dye penetrant inspection

C. Plugged Vessel Walls and Ducts.
Local Effects:
- Unequal gas distribution
- Poor conversion efficiency
- Potential cracking of shell
System Effects:
- If shell cracks, contamination hazard
- Wall scum may affect nearby compressors and pumps
Suggested Controls:
- Visual inspection
- Ultrasonic inspection

D. Fouled Heat Exchanger Tubes.
Local Effects:
- Converter efficiency greatly reduced
- Increase in internal gas temperature
- Possible damage of flanges and support grids
- Reaction heat out of control
- Eventually, total loss of function
System Effects:
- Extremely high gas temperatures can damage circulating pipes and downstream machines' seals
- If converter ceases working, the whole process will probably have to be shut down
Suggested Controls:
- Dye penetrant inspection
- Fluorescent (Zyglo) inspection
- Differential temperature control
**DISTILLATION TOWER** Ref. [1, 9, 16, 21, 45, 53, 63, 75]

A. Deformed or Broken Rings.
   Local Effects:
   - Ring migration
   - Rings may get caught in gate and control valve inlets
   - Equipment efficiency greatly reduced
   - Eventually, column will have to be shut down

   System Effects:
   - Other associated equipment like centrifugal pumps, and
     heaters may be seriously damaged by ring particles
   - Eventually, overall system will have to be shut down

   Suggested Controls:
   - Visual inspection
   - Material flow analysis

B. Unleveled Liquid Distributor.
   Local Effects:
   - Poor liquid distribution
   - Very low tower efficiency

   System Effects:
   - Poor distillate quality
   - No major impact expected

   Suggested Controls:
   - Visual inspection

C. Plugged or Corroded Distributor.
   Local Effects:
   - Fluid contamination
   - Reduced tower efficiency
   - Poor liquid distribution
   - Possible inappropriate column flooding

   System Effects:
   - Poor distillate quality
   - Pumps or compressors handling distillate
     may be slightly affected

   Suggested Controls:
   - Visual inspection
   - Column differential pressure analysis

D. Fouled Column Packing or Internals.
   Local Effects:
   - Premature or inappropriate column flooding
   - Deficient vapor flow
- Possible liquid drainage through chimneys
- Column efficiency greatly reduced

System Effects:
- Contamination hazard
- Fluid spillage may affect the normal functioning of nearby equipment
- Associated pumps and compressors may fail

Suggested Controls:
- Visual inspection
- Material flow analysis
- Column differential pressure analysis

**EVAPORATOR** Ref. [5, 63, 64, 68, 81, 90, 108]

A. Damaged Mechanical Seals in Stuffing Box of Pump.

Local Effects:
- Pump's capacity severely reduced
- Increase in pump vibration
- Contamination hazard
- Poor liquid circulation
- Heat exchanger tubes may get fouled
- Evaporator efficiency reduced

System Effects:
- If pumping fluid is toxic, contamination hazard
- Transmitted vibration may damage nearby machinery
- Corrosion problems may prevail in adjacent areas

Suggested Controls:
- Hydrostatic pressure test
- Visual inspection

B. Worn Impeller of Pump.

Local Effects:
- Pump's capacity severely reduced
- Increase in pump vibration
- Reduction in suction power
- Poor liquid circulation
- Heat exchanger tubes may get fouled
- Evaporator efficiency reduced

System Effects:
- Upstream ducts may get clogged
- Transmitted vibration may damage attached pipes or equipment
- Associated compressors and turbines may overload
Suggested Controls:
- Hydrostatic pressure test
- Flow analysis
- Visual inspection

C. Faulty Thrust Bearings of Pump.
Local Effects:
- Excessive pump vibration
- Pump motor may overload and run hot
- Possible shaft/gear misalignment
- Increase in shaft radial movement
- Eventual pump shut down
- Heat exchanger may get severely damaged
- Eventual system shut down
System Effects:
- Destructive equipment vibration
- If motor overloads, nearby equipment may experience electrical problems
- If pump ceases working, related equipment detriment should be expected
Suggested Controls:
- Pressure pulsation (piezoelectric pressure) test
- Visual inspection
- Vibration analysis
- Bearing temperature control

D. Deformed Shaft of Pump.
Local Effects:
- Pumping efficiency greatly reduced
- Excessive pump vibration
- Increase in shaft radial movement
- Possible pump bearings damage
- Possible pump seals damage
- Eventual pump couplings failure
- Circulation pipes may result deformed or bent
- Probable poor liquid flow through heating tubes
- Evaporator efficiency greatly affected
System Effects:
- Destructive equipment vibration
- Possible clogging of attached pipes
- Fluid leakage around shaft may increase, which could lead to contamination problems
Suggested Controls:
- Visual inspection
- Tensile stress analysis
- Pressure pulsation (piezoelectric pressure) test
- Vibration analysis

E. Leaking Casing of Pump.
Local Effects:
- Reduced pumping rate
- Contamination hazard
- Possible corrosion effects on pump elements
- Liquid loss
- Heat exchanger tubes may get fouled
- If leak persists, eventual evaporator shut down

System Effects:
- If pumping fluid is toxic, contamination hazard
- Auxiliary heating subsystem may get atrophied

Suggested Controls:
- Visual inspection
- Hydrostatic pressure test
- Flow analysis

F. Faulty Shaft Couplings of Pump.
Local Effects:
- Pump shaft misalignment
- Atrophied shaft movement
- Loss of pumping efficiency
- Increase in pump noise and vibration
- Possible pump seals damage
- Eventually, pump total shut down
- Circulation pipes may be deformed or bent
- Possible leaking of liquid from pipe joints
- Eventually, evaporator may have to be shut down

System Effects:
- Destructive equipment vibration
- If pump ceases working, related equipment detriment should be expected
- Possible clogging of attached pipes
- Fluid leakage around shaft may increase, which could lead to contamination problems

Suggested Controls:
- Visual inspection
- Vibration analysis
- Pressure pulsation (piezoelectric pressure) test

G. Faulty Impeller Wear Ring of Pump.
Local Effects:
- Internal liquid leakage from the pump discharge back the pump suction
- Eminent pump impeller wear
- Potential corrosion effect on pump's internals
- Pump's capacity greatly reduced
- If liquid circulation is affected, evaporator efficiency reduced

System Effects:
- Contamination hazard
- Possible clogging of attached pipes
- Downstream equipment may be detrimentally affected

Suggested Controls:
- Visual inspection
- Flow analysis
- Venturi analysis
- Hydrostatic pressure test

H. Broken Tube Support Baffles of Heat Exchanger.

Local Effects:
- May lead to tube breakage
- Liquid leakage to shell
- Liquid contamination
- Heat exchanger efficiency greatly reduced
- Eventual evaporator shut down

System Effects:
- If tube-side fluid is toxic, contamination hazard
- Process temperature may go out of control
- Related equipment such as pumps and compressors may be affected

Suggested Controls:
- Visual inspection

I. Cracked Tubes of Heat Exchanger.

Local Effects:
- Liquid leakage to shell
- Liquid contamination
- Heat exchanger efficiency greatly reduced
- Pump surge may occur
- Evaporator's elements may get completely wrecked

System Effects:
- If tube-side fluid is toxic, contamination hazard
- Process temperature may go out of control
- Related equipment such as pumps and compressors may be affected

Suggested Controls:
- Hydrostatic test
- Dye penetrant inspection
- Fluorescent (Zyglo) inspection
J. Deformed Impingement Plate of Heat Exchanger.
Local Effects:
- Potential erosive effect on tubes
- Evaporator efficiency should not be affected
System Effects:
- No major impact on downstream machines should be expected
Suggested Controls:
- Visual inspection

K. Fouled Tubes of Heat Exchanger
Local Effects:
- Potential cracking of tubes
- Poor heat transfer efficiency
- Possible damage to support baffles
- Liquid evaporation efficiency reduced
- If tubes crack, possible system wreck
System Effects:
- If tube-side fluid is toxic and tubes crack, contamination hazard
- Process temperature may go out of control
- Related equipment such as pumps and compressors may be affected
Suggested Controls:
- Eddy current inspection
- Ultrasonic inspection

L. Corroded Exchanger and Kettle Surfaces.
Local Effects:
- Apparatus efficiency greatly reduced
- Liquid contamination
- Liquid evaporation efficiency reduced
System Effects:
- Process temperature may go out of control
- Kettle scum may atrophy attached pipes and pumps
Suggested Controls:
- Visual inspection
- Eddy current inspection

M. Plugged or Corroded Vapor Heads Walls.
Local Effects:
- Vapor entrainment
- Loss of evaporation efficiency
System Effects:
- Attached vents and ducts can be damaged
- No major effects on process should be expected
Suggested Controls:
- Visual inspection
- Ultrasonic inspection

N. Leaking Circulation Pipe Joints.
Local Effects:
- Damage to external heat exchanger
- Potential pump surge
- Eventual evaporator shut down
System Effects:
- Contamination hazard
- Flow pressure loss may affect the normal operation of downstream pumps, compressors or distillation columns
- If evaporator ceases working, overall process may have to be shut down
Suggested Controls:
- Visual inspection
- Radioactive isotope injection

O. Plugged Tube Inlets.
Local Effects:
- Liquid contamination
- Possible fouling of heat exchanger tubes
- Evaporator efficiency greatly reduced
System Effects:
- Contamination hazard
- Clogged inlets may affect the normal operation of downstream pumps, compressors or distillation towers
- If evaporator ceases working, overall process may have to be shut down
Suggested Controls:
- Visual inspection
- Ultrasonic inspection

HEAT EXCHANGER Ref. [16, 27, 29, 53, 61, 83]

A. Broken Tube Support Baffles.
Local Effects:
- May lead to tube breakage
- Cooling medium leakage to shell
- Substance contamination
- Heat exchanger efficiency greatly reduced
- Eventual equipment shut down
System Effects:
- If tube-side fluid is toxic, contamination hazard
- Process temperature may go out of control
- Related equipment such as pumps and compressors may be affected
Suggested Controls:
- Visual inspection

B. Cracked Tubes.
Local Effects:
- Cooling medium leakage to shell
- Substance contamination
- Heat exchanger efficiency greatly reduced
- Apparatus may get completely wrecked
System Effects:
- If tube-side fluid is toxic, contamination hazard
- Process temperature may go out of control
- Related equipment such as pumps and compressors may be affected
- If exchanger stops working, entire process may have to be shut down
Suggested Controls:
- Hydrostatic Test
- Dye penetrant inspection
- Fluorescent (Zyglo) inspection

C. Deformed Impingement Plate.
Local Effects:
- Potential erosive effect on tubes
System Effects:
- No major impact on downstream machines should be expected
Suggested Controls:
- Visual inspection

D. Fouled Tubes.
Local Effects:
- Potential cracking of tubes
- Poor heat transfer efficiency
- Possible damage to support baffles
System Effects:
- If tube-side fluid is toxic and tubes crack, contamination hazard
- Process temperature may go out of control
- Related equipment such as pumps and compressors may be affected
Suggested Controls:
- Eddy current inspection
- Ultrasonic inspection

E. Corroded Exchanger and Kettle Surfaces.
Local Effects:
- Apparatus efficiency greatly reduced
- Substance contamination
System Effects:
- Process temperature may go out of control
- Kettle scum may atrophy attached pipes and pumps
Suggested Controls:
- Visual inspection
- Eddy current inspection

MULTISTAGE COMPRESSOR Ref. [10, 13, 56, 63, 77, 78]

A. Deformed Thrust Bearings.
Local Effects:
- Increase of axial rotor movement
- Spinning wheel may touch a stationary element
- Compressor internals may wreck
System Effects:
- Wheel pieces may tear through case and cause human injuries
- Wheel debris may damage downstream equipment
Suggested Controls:
- Visual inspection
- Vibration analysis
- Mechanical running test

B. Plugged Stationary Elements.
Local Effects:
- Loss of gas compression efficiency
- Increase in discharge temperature
- Motor amp load may go down
- Possible unbalance of the rotor
System Effects:
- Inefficient gas compression may lead to abnormal performance of downstream equipment
- Increase in discharge temperature may damage attached equipment nozzles and seals
Suggested Controls:
- Visual inspection
- Ultrasonic inspection

C. Eroded Impellers Exit Tips.
Local Effects:
- Loss of compression efficiency
- May cause shaft unbalance
- Increase in equipment vibration
System Effects:
- Transmitted vibration may damage nearby equipment
- Inefficient gas compression may lead to abnormal performance of downstream equipment
Suggested Controls:
- Visual inspection
- Eddy current inspection

D. Damaged Shaft and Interstage (Labyrinth) Seals.
Local Effects:
- Gas compression efficiency greatly reduced
- Gas leakage
- Possible increase in element corrosion
- Possible diaphragms deformation
System Effects:
- Inefficient gas compression may lead to abnormal performance of downstream equipment
- If compressed gas is toxic or corrosive, contamination or corrosion problems may developed in nearby machine areas
Suggested Controls:
- Static gas test
- Dye penetrant inspection
- Fluorescent (Zyglo) inspection

E. Misaligned Shaft.
Local Effects:
- Excessive equipment vibration and noise
- Eventually, total loss of compression function
- Possible damage to labyrinth seals
- Compressor internals most likely to wreck
System Effects:
- Transmitted vibration may damage nearby equipment
- Inefficient gas compression may lead to abnormal performance of downstream equipment
Suggested Controls:
- Vibration analysis
- Visual inspection
- Ultrasonic inspection
- Mechanical running test

**PIPE** Ref. [28, 70, 73, 94, 103]

A. Leaking Fittings or Joints.
   Local Effects:
   - Pressure loss
   - Possible corrosion effect on outer wall and fittings
   System Effects:
   - Contamination hazard
   - Possible damage to attached equipment
   - Depending on process, downstream machines may be seriously affected
   Suggested Controls:
   - Visual inspection
   - Radioactive isotope injection
   - Gas detector

B. Cracked Pipe Due To Over-stress.
   Local Effects:
   - Potential fluid leakage
   - Pressure and temperature loss
   System Effects:
   - Contamination hazard
   - Connected equipment may be greatly damaged
   - Possible corrosion problems in the area
   - If leakage is considerable, overall system may be stopped
   Suggested Controls:
   - Eddy current inspection
   - Radioactive isotope injection
   - Tensile stress test

C. Plugged Inner Section.
   Local Effects:
   - Obstructed flow
   - Eventual cracking of pipe
   System Effects:
   - Connected equipment may be damaged
   - If obstruction is considerable or cracking precipitates, entire process may have to be shut down
Suggested Controls:
- Ultrasonic inspection
- Flow pressure analysis

D. Bent Pipe.
Local Effects:
- Possible cracking of pipe
- Damage to support hardware
- Possible resulting leakage at fitting locations
System Effects:
- Eminent damage to attached equipment
Suggested Controls:
- Visual inspection

E. Corroded or Eroded Inner Wall.
Local Effects:
- Development of "hot spots" on piping wall
- Eventual pipe fracture
- Fluid contamination
System Effects:
- Contaminated fluid may affect the normal functioning of downstream machinery
Suggested Controls:
- Ultrasonic inspection
- Eddy current inspection

REACTOR Ref. [7, 64, 65, 96, 101, 111]
A. Worn or faulty Stirrer Couplings.
Local Effects:
- Possible excessive vibration
- Loss of mixing efficiency
- Poor reaction process
System Effects:
- Nearby equipment may be affected by transmitted vibration
- Possible bending of attached piping
Suggested Controls:
- Visual inspection
- Magnetic particle inspection

B. Non-lubricated Drive Bearings and Gears.
Local Effects:
- Increase in equipment vibration
- Possible gear misalignment
- Eventual overheating of stirrer motor
- May lead to reactor shut down

System Effects:
- If reactor functioning does not stop, no major impact on overall system should be expected

Suggested Controls:
- Visual inspection
- Lubrication records
- Moisture tests

C. Damaged Discharged Nozzle Seals.

Local Effects:
- Internal pressure loss
- Reactor efficiency reduced
- Liquid leakage
- Reaction quality affected

System Effects:
- Contamination hazard
- Associated pumps, heating system, and pipes are likely to fail
- If liquid is toxic, overall system must be shut down

Suggested Controls:
- Visual inspection
- Vessel pressure control

D. Defective Heating Coils.

Local Effects:
- Inappropriate heating of mixture
- Poor or failed reaction

System Effects:
- If reaction failed, entire processed material batch is most likely to be lost
- No major impact on nearby machines' functioning should be expected

Suggested Controls:
- Temperature detectors (thermocouples & electrical resistance detectors)
- Visual inspection
- Amps meter
WASTE HEAT BOILER  Ref. [2, 9, 16, 45, 63, 78, 109]

A. Broken Expansion Joints.
   Local Effects:
   - Tube deformation
   - Possible heating medium leakage into water
   - Substance contamination
   - Equipment efficiency greatly reduced
   System Effects:
   - Product quality greatly affected
   - If water is circulated, major equipment damage and contamination should be expected in nearby areas
   - Heating sub-system components may get wrecked
   Suggested Controls:
   - Visual inspection
   - Hydrostatic test

B. Fouled Tubes.
   Local Effects:
   - Heating medium leakage into boiling water
   - Substance contamination
   - Equipment efficiency greatly reduced
   System Effects:
   - Product quality greatly affected
   - If water is circulated, major equipment damage and contamination should be expected in nearby areas
   - Heating sub-system components may get wrecked
   Suggested Controls:
   - Ultrasonic inspection
   - Differential temperature analysis
   - Magnetic particle inspection
   - Eddy current inspection

C. Deformed Demister Mesh Pad.
   Local Effects:
   - Poor steam quality
   - Small droplets of water in steam
   System Effects:
   - Increased corrosion in steam ducts
   - If steam turbines attached, their efficiency will be affected
   Suggested Controls:
   - Visual inspection
D. Cracked Boiler Drum Shell.

Local Effects:
- Total loss of equipment function
- Water leakage from shell
- Eventual fouling of tubes

System Effects:
- Product quality greatly affected
- If water is circulated, major equipment damage and contamination should be expected in nearby areas
- Heating sub-system components may get wrecked
- Spilled water may damage nearby equipment such as motors, screens, and gears
- Overall system shut down very likely

Suggested Controls:
- Hydrostatic test
- Dye penetrant inspection
- Fluorescent (Zyglo) inspection
- Eddy current inspection
APPENDIX C

PRECIPITATING FACTORS

The information included in this appendix was obtained by series of interviews conducted with doctoral students of the department of Chemical Engineering at the University of Alabama. Specialized equipment maintenance literature was also consulted.

BURNER Ref. [9, 21, 23, 24, 25, 53, 63, 86, 108]

A. Obstructed Inlet or Outlet Ducts of Blower.
Critical Factors:
a. Abrasive substances like dust, fly ash, and sand in gas [0.005 to 20 grains/ft³]
   Important Factors:
a. Gas density [0.1 to 0.6 lb/ft³]
   Related Factors:
a. Humidity [50 to 100%]

B. Cracked Inlet Box of Blower.
Critical Factors:
a. Gas temperature [300 to 600 °F]
b. High pressure head [1.5 to 8 psi]
   Important Factors:
a. High rotor speed [2000 to 3500 rpm]
b. H₂SO₄ partial pressure [0.15 to 75 psi]
c. CO₂ partial pressure [1.5 to 150 psi]
   Related Factors:
a. Humidity [50 to 100%]

C. Misaligned Wheel Bearings of Blower.
Critical Factors:
a. High pressure head [1.5 to 6 psi]
b. High rotor speed [2000 to 4500 rpm]
   Important Factors:
a. Gas temperature [200 to 500 °F]
   Related Factors:
a. Gas density [0.08 to 0.5 lb/ft³]

D. Cracked Wheel of Blower.
Critical Factors:
a. High pressure head [1.5 to 6 psi]

**Important Factors:**

a. Gas temperature [600 to 850 °F]
b. $\text{H}_2\text{SO}_4$ partial pressure [0.15 to 75 psi]
c. $\text{CO}_2$ partial pressure [1.5 to 150 psi]

**Related Factors:**

a. Humidity [50 to 100%]

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**E. Damaged Shaft Seals of Blower.**

**Critical Factors:**

a. Abrasive substances like sand, fly ash, dust, etc, in gas [0.005 to 20 grains/ft$^3$]
b. Gas temperature [200 to 500 °F]

**Important Factors:**

a. High rotor speed [2000 to 4500 rpm]
b. $\text{H}_2\text{SO}_4$ partial pressure [0.15 to 75 psi]
c. $\text{CO}_2$ partial pressure [1.5 to 150 psi]

**Related Factors:**

a. Humidity [50 to 100%]

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**F. Expanded Shaft of Blower.**

**Critical Factors:**

a. Gas temperature [300 to 700 °F]

**Important Factors:**

a. High rotor speed [1500 to 4000]
b. High head pressure [2 to 5 psi]

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**G. Worn Wheel Blades of Blower.**

**Critical Factors:**

a. Abrasive substances like sand, fly ash, dust, etc, in gas [0.005 to 20 grains/ft$^3$]

**Important Factors:**

a. High rotor speed [2000 to 4500 rpm]
b. $\text{H}_2\text{SO}_4$ partial pressure [0.15 to 75 psi]
c. $\text{CO}_2$ partial pressure [1.5 to 150 psi]
d. Gas temperature [300 to 500 °F]

**Related Factors:**

a. Gas density [0.1 to 0.6 lb/ft$^3$]

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**H. Misaligned Couplings Inlet Bells of Blower.**

**Critical Factors:**

a. High rotor speed [3000 to 5000 rpm]

**Important Factors:**

a. High head pressure [2 to 5 psi]
b. Gas temperature [300 to 500 °F]

**Related Factors:**

a. Gas density [0.08 to 0.5 lb/ft$^3$]
I. Worn Scroll and Housing Liners of Blower.

Critical Factors:
- Abrasive substances like sand, fly ash, dust, etc., in gas [0.005 to 20 grains/ft³]

Important Factors:
- H₂SO₄ partial pressure [0.15 to 75 psi]
- CO₂ partial pressure [1.5 to 150 psi]
- Gas temperature [200 to 600 °F]

Related Factors:
- Gas density [0.08 to 0.5 lb/ft³]
- Humidity [50 to 100%]

J. Damaged Mechanical Seals in Stuffing Box of Pump.

Critical Factors:
- Abrasive fluid [1 to 10% solids by weight]
- PV factor [35000 to 70000 psi * ft/min]

Important Factors:
- Fluid temperature [100 to 750 °F]
- Fluid pH [4 to 0 and 10 to 14]

Related Factors:
- Impeller speed [3000 to 6000 rpm]
- Fluid viscosity [150 to 1000 SSU]

K. Worn Impeller of Pump.

Critical Factors:
- Abrasive fluid [1 to 8% solids by weight]

Important Factors:
- Fluid temperature [200 to 400 °F]
- Fluid pH [4 to 0 and 10 to 14]

Related Factors:
- Impeller speed [1200 to 5000 rpm]
- Fluid viscosity [150 to 800 SSU]

L. Faulty Thrust Bearings of Pump.

Critical Factors:
- Combined stress on bearings [1000 to 5000 psi]

Important Factors:
- Fluid temperature [120 to 300 °F or 40 to 0 °F]
- Impeller speed [1500 to 5000 rpm]

Related Factors:
- Humidity [60 to 100%]

M. Deformed Shaft of Pump.

Critical Factors:
- Impeller speed [1000 to 4500 rpm]
- Combined stress on shaft [1500 to 6000 psi]
Important Factors:
  a. Fluid temperature [300 to 650 °F or 20 to 0 °F]
Related Factors:
  a. Suction pressure [10 to 30 psi]
  b. Fluid pH [4 to 0 and 10 to 14]
  c. Fluid viscosity [100 to 1000 SSU]

N. Leaking Casing of Pump.
Critical Factors:
  a. PV factor [4000 to 70000 psi * ft/min]
Important Factors:
  a. Fluid temperature [150 to 400 °F]
  b. Fluid pH [4 to 0 and 10 to 14]
Related Factors:
  a. Suction pressure [15 to 50 psi]

O. Faulty Shaft Couplings of Pump.
Critical Factors:
  a. Combined stress on shaft [2000 to 7000 psi]
Important Factors:
  a. Impeller speed [1000 to 5000 rpm]
  b. Fluid temperature [150 to 700 °F]
Related Factors:
  a. Humidity [80 to 100%]
  b. Fluid viscosity [100 to 1000 SSU]

P. Faulty Impeller Wear Ring of Pump.
Critical Factors:
  a. Abrasive fluid [1 to 10 % solids by weight]
Important Factors:
  a. Impeller speed [3000 to 4500 rpm or 1500 to 700 rpm]
Related Factors:
  a. Fluid temperature [200 to 500 °F]
  b. Fluid viscosity [200 to 1000 SSU]

Q. Plugged Spray Nozzle in Combustion Chamber.
Critical Factors:
  a. Abrasive substances in air [0.05 to 20 grains/ft³]
  b. Abrasive substances in liquid fuel [0.1 to 2% solids by weight]
Important Factors:
  a. Low air rate [750 to 550 ft³/min]
  b. Flame temperature [1200 to 1700 °F]
Related Factors:
  a. Low atomizing pressure [4 to 2 psi]
  b. Low operating liquid rate [30 to 15 short tons/day]
R. Carbonaceous Matter Formation in Combustion Chamber.

Critical Factors:
- a. Ash content in liquid fuel [0.05 to 0.1% solids by weight]
- b. Carbon dioxide content in burner gas [0.27 to 0.8% of total volume]
- c. Carbon content in liquid fuel [0.5 to 1% solids by weight]

Important Factors:
- a. Abrasive substances in air [0.05 to 20 grains/ft\(^3\)]

Related Factors:
- a. High air rate [550 to 750 ft\(^3\)/min]
- b. High operating liquid rate [15 to 30 short tons/day]

CENTRIFUGAL BLOWER Ref. [10, 16, 77, 53, 64, 78]

A. Obstructed Inlet or Outlet Ducts.

Critical Factors:
- a. Abrasive substances like dust, fly ash, and sand in gas [0.005 to 20 grains/ft\(^3\)]

Important Factors:
- a. Gas density [0.1 to 0.6 lb/ft\(^3\)]

Related Factors:
- a. Humidity [50 to 100%]

B. Cracked Inlet Box.

Critical Factors:
- a. Gas temperature [300 to 600 °F]
- b. High pressure head [1.5 to 8 psi]

Important Factors:
- a. High rotor speed [2000 to 3500 rpm]
- b. H\(_2\)S\(_2\)O\(_5\) partial pressure [0.15 to 75 psi]
- c. CO\(_2\) partial pressure [1.5 to 150 psi]

Related Factors:
- a. Humidity [50 to 100%]

C. Misaligned Wheel Bearings.

Critical Factors:
- a. High pressure head [1.5 to 6 psi]
- b. High rotor speed [2000 to 4500 rpm]

Important Factors:
- a. Gas temperature [200 to 500 °F]

Related Factors:
- a. Gas density [0.08 to 0.5 lb/ft\(^3\)]

D. Cracked Wheel.

Critical Factors:
- a. High pressure head [1.5 to 6 psi]
Important Factors:
- Gas temperature [600 to 850 °F]
- $\text{H}_2\text{SO}_4$ partial pressure [0.15 to 75 psi]
- $\text{CO}_2$ partial pressure [1.5 to 150 psi]

Related Factors:
- Humidity [50 to 100%]

**E. Damaged Shaft Seals.**

Critical Factors:
- Abrasive substances like sand, fly ash, dust, etc, in gas [0.005 to 20 grains/ft$^3$]
- Gas temperature [200 to 500 °F]

Important Factors:
- High rotor speed [2000 to 4500 rmp]
- $\text{H}_2\text{SO}_4$ partial pressure [0.15 to 75 psi]
- $\text{CO}_2$ partial pressure [1.5 to 150 psi]

Related Factors:
- Humidity [50 to 100%]

**F. Expanded Shaft.**

Critical Factors:
- Gas temperature [300 to 700 °F]

Important Factors:
- High rotor speed [1500 to 4000]
- High head pressure [2 to 5 psi]

**G. Worn Wheel Blades.**

Critical Factors:
- Abrasive substances like sand, fly ash, dust, etc, in gas [0.005 to 20 grains/ft$^3$]

Important Factors:
- High rotor speed [2000 to 4500 rmp]
- $\text{H}_2\text{SO}_4$ partial pressure [0.15 to 75 psi]
- $\text{CO}_2$ partial pressure [1.5 to 150 psi]
- Gas temperature [300 to 500 °F]

Related Factors:
- Gas density [0.1 to 0.6 lb/ft$^3$]

**H. Misaligned Couplings Inlet Bells.**

Critical Factors:
- High rotor speed [3000 to 5000 rpm]

Important Factors:
- High head pressure [2 to 5 psi]
- Gas temperature [300 to 500 °F]

Related Factors:
- Gas density [0.08 to 0.5 lb/ft$^3$]
I. Worn Scroll and Housing Liners.

Critical Factors:
a. Abrasive substances like sand, fly ash, dust, etc, in gas [0.005 to 20 grains/ft³]

Important Factors:
a. H₂SO₄ partial pressure [0.15 to 75 psi]
b. CO₂ partial pressure [1.5 to 150 psi]
c. Gas temperature [200 to 600 °F]

Related Factors:
a. Gas density [0.08 to 0.5 lb/ft³]
b. Humidity [50 to 100%]

CENTRIFUGAL PUMP  Ref. [8, 15, 41, 42, 74, 86, 89, 108]

A. Damaged Mechanical Seals in Stuffing Box.

Critical Factors:
a. Abrasive fluid [1 to 10% solids by weight]
b. PV factor [35000 to 70000 psi * ft/min]

Important Factors:
a. Fluid temperature [100 to 750 °F]
b. Fluid pH [4 to 0 and 10 to 14]

Related Factors:
a. Impeller speed [3000 to 6000 rpm]
b. Fluid viscosity [150 to 1000 SSU]

B. Worn Impeller.

Critical Factors:
a. Abrasive fluid [1 to 8 % solids by weight]

Important Factors:
a. Fluid temperature [200 to 400 °F]
b. Fluid pH [4 to 0 and 10 to 14]

Related Factors:
a. Impeller speed [1200 to 5000 rpm]
b. Fluid viscosity [150 to 800 SSU]

C. Faulty Thrust Bearings.

Critical Factors:
a. Combined stress on bearings [1000 to 5000 psi]

Important Factors:
a. Fluid temperature [120 to 300 °F or 40 to 0 °F]
b. Impeller speed [1500 to 5000 rpm]

Related Factors:
a. Humidity [60 to 100%]
D. Deformed Shaft.
Critical Factors:
a. Impeller speed [1000 to 4500 rpm]
b. Combined stress on shaft [1500 to 6000 psi]
Important Factors:
a. Fluid temperature [300 to 650 °F or 20 to 0 °F]
Related Factors:
a. Suction pressure [10 to 30 psi]
b. Fluid pH [4 to 0 and 10 to 14]
c. Fluid viscosity [100 to 1000 SSU]

E. Leaking Casing.
Critical Factors:
a. PV factor [4000 to 70000 psi * ft/min]
Important Factors:
a. Fluid temperature [150 to 400 °F]
b. Fluid pH [4 to 0 and 10 to 14]
Related Factors:
a. Suction pressure [15 to 50 psi]

F. Faulty Shaft Couplings.
Critical Factors:
a. Combined stress on shaft [2000 to 7000 psi]
Important Factors:
a. Impeller speed [1000 to 5000 rpm]
b. Fluid temperature [150 to 700 °F]
Related Factors:
a. Humidity [80 to 100%]
b. Fluid viscosity [100 to 1000 SSU]

G. Faulty Impeller Wear Ring.
Critical Factors:
a. Abrasive fluid [1 to 10 % solids by weight]
Important Factors:
a. Impeller speed [3000 to 4500 rpm or 1500 to 700 rpm]
Related Factors:
a. Fluid temperature [200 to 500 °F]
b. Fluid viscosity [200 to 1000 SSU]

CONVERTER Ref. [21, 23, 45, 51, 63, 64]

A. Damaged Supporting Grids.
Critical Factors:
a. Gas temperature [700 to 1000 °F]
b. Catalyst weight [500 to 3000 lb]

Important Factors:
a. Abrasive substances like sand, fly ash, dust, etc, in gas [0.2 to 10 grains/ft³]

Related Factors:
a. Catalyst pH [4 to 0 and 10 to 14]
b. $\text{H}_2\text{SO}_4$ partial pressure [0.15 to 75 psi]
c. $\text{CO}_2$ partial pressure [1.5 to 150 psi]

B. Corroded or Cracked Supporting Flanges.

Critical Factors:
a. Abrasive substances like sand, fly ash, dust, etc, in gas [0.1 to 8 grains/ft³]
b. Catalyst weight [1000 to 2000 lb]

Important Factors:
a. Gas temperature [500 to 1000 °F]
b. $\text{H}_2\text{SO}_4$ partial pressure [0.15 to 75 psi]
c. $\text{CO}_2$ partial pressure [1.5 to 150 psi]

Related Factors:
a. Gas density [0.15 to 0.7 lb/ft³]

C. Plugged Vessel Walls and Ducts.

Critical Factors:
a. Abrasive substances like sand, fly ash, dust, etc., in gas [0.1 to 8 grains/ft³]

Important Factors:
a. Gas temperature [700 to 1000 °F]
b. $\text{H}_2\text{SO}_4$ partial pressure [0.15 to 75 psi]
c. $\text{CO}_2$ partial pressure [1.5 to 150 psi]
d. Averaged total gas mass velocity [60 to 100 ft³/min/ft²]

Related Factors:
a. Gas density [0.08 to 0.6 lb/ft³]
b. Humidity [75 to 100%]

D. Fouled Heat Exchanger Tubes.

Critical Factors:
a. Abrasive substances like sand, fly ash, dust, etc., in gas [0.1 to 10 grains/ft³]
b. Gas velocity inside heat exchanger tubes [80 to 40 ft³/min/ft²]

Important Factors:
a. Gas temperature [300 to 900 °F]
b. $\text{H}_2\text{SO}_4$ partial pressure [0.15 to 75 psi]
c. $\text{CO}_2$ partial pressure [1.5 to 150 psi]

Related Factors:
a. Gas density [0.1 to 0.7 lb/ft³]
DISTILLATION TOWER  Ref. [1, 9, 16, 21, 45, 53, 63, 75]

A. Deformed or Broken Rings.
   Critical Factors:
   a. High column holdup [10 to 30%]
   Important Factors:
   a. Average tower top pressure drop [10 to 20%]
   Related Factors:
   a. Leaving liquid temperature [20 to -20 °F or 150 to 300 °F]

B. Unleveled Liquid Distributor.
   Critical Factors:
   a. Start-up pressure surge [0.5 to 1 psi]
   Important Factors:
   a. Fed liquid rate [3000 to 10000 lb/ft² per hr]
   Related Factors:
   a. Fed liquid viscosity [800 to 3000 SSU]

C. Plugged or Corroded Distributor.
   Critical Factors:
   a. Low fed liquid rate [2000 to 500 lb/ft² per hr]
   b. Abrasive substances (slurry) in liquid [5 to 20% solids by weight]
   Important Factors:
   a. Liquid pH [4 to 0 or 10 to 14]
   Related Factors:
   a. Fed liquid viscosity [800 to 3000 SSU]

D. Fouled Column Packing or Internals.
   Critical Factors:
   a. Abrasive substances (slurry) in liquid input mixture [5 to 20% solids by weight]
   Important Factors:
   a. Fed liquid pH [4 to 0 or 10 to 14]
   b. H₂SO₄ partial pressure in leaving gas [0.15 to 75 psi]
   c. CO₂ partial pressure in leaving gas [1.5 to 150 psi]
   Related Factors:
   a. Fed liquid viscosity [500 to 2500 SSU]

EVAPORATOR  Ref. [5, 63, 64, 68, 81, 90, 108]

A. Damaged Mechanical Seals in Stuffing Box of Pump.
   Critical Factors:
   a. Abrasive fluid [1 to 10% solids by weight]
   b. PV factor [35000 to 70000 psi * ft/min]
Important Factors:
a. Fluid temperature [100 to 750 °F]
b. Fluid pH [4 to 0 and 10 to 14]

Related Factors:
a. Impeller speed [3000 to 6000 rpm]
b. Fluid viscosity [150 to 1000 SSU]

B. Worn Impeller of Pump.
Critical Factors:
a. Abrasive fluid [1 to 8 % solids by weight]

Important Factors:
a. Fluid temperature [200 to 400 °F]
b. Fluid pH [4 to 0 and 10 to 14]

Related Factors:
a. Impeller speed [1200 to 5000 rpm]
b. Fluid viscosity [150 to 800 SSU]

C. Faulty Thrust Bearings of Pump.
Critical Factors:
a. Combined stress on bearings [1000 to 5000 psi]

Important Factors:
a. Fluid temperature [120 to 300 °F or 40 to 0 °F]
b. Impeller speed [1500 to 5000 rpm]

Related Factors:
a. Humidity [60 to 100%]

D. Deformed Shaft of Pump.
Critical Factors:
a. Impeller speed [1000 to 4500 rpm]
b. Combined stress on shaft [1500 to 6000 psi]

Important Factors:
a. Fluid temperature [300 to 650 °F or 20 to 0 °F]

Related Factors:
a. Suction pressure [10 to 30 psi]
b. Fluid pH [4 to 0 and 10 to 14]
c. Fluid viscosity [100 to 1000 SSU]

E. Leaking Casing of Pump.
Critical Factors:
a. PV factor [4000 to 70000 psi * ft/min]

Important Factors:
a. Fluid temperature [150 to 400 °F]
b. Fluid pH [4 to 0 and 10 to 14]

Related Factors:
a. Suction pressure [15 to 50 psi]
F. Faulty Shaft Couplings of Pump.

Critical Factors:
a. Combined stress on shaft [2000 to 7000 psi]

Important Factors:
a. Impeller speed [1000 to 5000 rpm]
b. Fluid temperature [150 to 700 °F]

Related Factors:
a. Humidity [80 to 100%]
b. Fluid viscosity [100 to 1000 SSU]

G. Faulty Impeller Wear Ring of Pump.

Critical Factors:
a. Abrasive fluid [1 to 10 % solids by weight]

Important Factors:
a. Impeller speed [3000 to 4500 rpm or 1500 to 700 rpm]

Related Factors:
a. Fluid temperature [200 to 500 °F]
b. Fluid viscosity [200 to 1000 SSU]

H. Broken Tube Support Baffles of Heat Exchanger.

Critical Factors:
a. Shell-side liquid or gas temperature [250 to 500 °F]

Important Factors:
a. Shell-side liquid cross flow velocity [8 to 12 ft/s]
b. Shell-side gas pressure [50 to 500 psi]
c. Shell-side gas H₂SO₄ partial pressure [0.15 to 75 psi]
d. Shell-side gas CO₂ partial pressure [1.5 to 150 psi]

Related Factors:
a. Shell-side fluid viscosity [150 to 800 SSU]
b. Shell-side gas density [0.1 to 0.6 lb/ft³]

I. Cracked Tubes of Heat Exchanger.

Critical Factors:
a. Tube-side temperature [30 to -100 °F]
b. Shell-side temperature [300 to 500 °F]

Important Factors:
a. Tube-side fluid cross flow velocity [7 to 15 ft/s]
b. Abrasive substances in shell-side gas [0.1 to 20 grains/ft³]
c. Abrasive substances in shell-side fluid [2 to 10% solids by weight]
d. Abrasive substances in tube-side fluid [2 to 10% solids by weight]

Related Factors:
a. Shell-side fluid cross flow velocity [9 to 15 ft/s]
b. Shell-side gas pressure [50 to 500 psi]
J Deformed Impingement Plate of Heat Exchanger.
Critical Factors:
- a. Shell-side fluid cross flow velocity [9 to 15 ft/s]
- b. Shell-side gas pressure [50 to 500 psi]
Important Factors:
- a. Shell-side temperature [150 to 800 °F]
- b. Abrasive substances in shell-side gas [0.1 to 20 grains/ft³]
- c. Abrasive substances in shell-side fluid [2 to 10% solids by weight]
Related Factors:
- a. Shell-side fluid cross flow velocity [9 to 15 ft/s]
- b. Shell-side gas pressure [50 to 500 psi]

K Fouled Tubes of Heat Exchanger.
Critical Factors:
- a. Shell-side liquid or gas temperature [150 to 800 °F]
- b. Abrasive substances in shell-side gas [0.1 to 20 grains/ft³]
- c. Abrasive substances in shell-side fluid [1 to 8% solids by weight]
Important Factors:
- a. Low shell-side liquid cross flow velocity [15 to 3 ft/s]
- b. Tube-side fluid pH [4 to 0 or 10 to 14]
- c. Shell-side gas H₂SO₄ partial pressure [0.15 to 75 psi]
- d. Shell-side gas CO₂ partial pressure [1.5 to 150 psi]
Related Factors:
- a. Shell-side fluid viscosity [100 to 700 SSU]
- b. Tube-side fluid viscosity [100 to 700 SSU]
- c. Shell-side gas density [0.1 to 0.5 lb/ft³]

L. Corroded Exchanger and Kettle Surfaces.
Critical Factors:
- a. Tube-side fluid pH [4 to 0 or 10 to 14]
- b. Shell-side gas H₂SO₄ partial pressure [0.15 to 75 psi]
- c. Shell-side gas CO₂ partial pressure [1.5 to 150 psi]
Important Factors:
- a. Shell-side liquid cross flow velocity [7 to 13 ft/s]
- b. Atmospheric humidity [80 to 100%]
Related Factors:
- a. Shell-side fluid viscosity [100 to 500 SSU]
- b. Tube-side fluid viscosity [100 to 500 SSU]
- c. Shell-side gas density [0.1 to 0.5 lb/ft³]

M. Plugged or Corroded Vapor Heads Walls.
Critical Factors:
- a. Abrasive substance in final liquor [1 to 8% solids by weight]
Important Factors:
- a. Liquor pH [4 to 0 and 10 to 14]
b. Liquor temperature [100 to 350 °F]

Related Factors:

a. Final liquor viscosity [800 to 3000 SSU]

N. Leaking Circulation Pipe Joints.

Critical Factors:

a. Liquor temperature [200 to 750 °F]
b. Average fluid pressure in circulation pipe [100 to 500 psi]

Important Factors:

a. Average fluid cross flow velocity in pipe [10 to 20 ft/s]

Related Factors:

a. Liquor pH [4 to 0 or 10 to 14]

O. Plugged Tube Inlets.

Critical Factors:

a. Abrasive substance in final liquor [3 to 10% solids by weight]

Important Factors:

a. Average temperature in circulation pipe [150 to 300 °F]
b. Average cross flow velocity in circulation pipe [9 to 5 ft/s]

Related Factors:

a. Final liquor viscosity [800 to 3000 SSU]

HEAT EXCHANGER  Ref. [16, 27, 29, 53, 61, 83]

A. Broken Tube Support Baffles.

Critical Factors:

a. Shell-side liquid or gas temperature [250 to 500 °F]

Important Factors:

a. Shell-side liquid cross flow velocity [8 to 12 ft/s]
b. Shell-side gas pressure [50 to 500 psi]
c. Shell-side fluid pH [4 to 0 or 10 to 14]
d. Shell-side gas H₂SO₄ partial pressure [0.15 to 75 psi]
e. Shell-side gas CO₂ partial pressure [1.5 to 150 psi]

Related Factors:

a. Shell-side fluid viscosity [150 to 800 SSU]
b. Shell-side gas density [0.1 to 0.6 lb/ft³]

B. Cracked Tubes.

Critical Factors:

a. Tube-side temperature [30 to -100 °F]
b. Shell-side temperature [300 to 500 °F]

Important Factors:

a. Tube-side fluid cross flow velocity [7 to 15 ft/s]
b. Abrasive substances in shell-side gas [0.1 to 20 grains/ft³]
c. Abrasive substances in shell-side fluid [2 to 10% solids by weight]
d. Abrasive substances in tube-side fluid [2 to 10% solids by weight]

Related Factors:
- a. Shell-side fluid cross flow velocity [9 to 15 ft/s]
- b. Shell-side gas pressure [50 to 500 psi]

C. Deformed Impingement Plate.

Critical Factors:
- a. Shell-side fluid cross flow velocity [9 to 15 ft/s]
- b. Shell-side gas pressure [50 to 500 psi]

Important Factors:
- a. Shell-side temperature [150 to 800 °F]
- b. Abrasive substances in shell-side gas [0.1 to 20 grains/ft³]
- c. Abrasive substances in shell-side fluid [2 to 10% solids by weight]

Related Factors:
- a. Shell-side fluid cross flow velocity [9 to 15 ft/s]
- b. Shell-side gas pressure [50 to 500 psi]

D. Fouled Tubes.

Critical Factors:
- a. Shell-side liquid or gas temperature [150 to 800 °F]
- b. Abrasive substances in shell-side gas [0.1 to 20 grains/ft³]
- c. Abrasive substances in shell-side fluid [1 to 8% solids by weight]

Important Factors:
- a. Low shell-side liquid cross flow velocity [15 to 3 ft/s]
- b. Tube-side fluid pH [4 to 0 or 10 to 14]
- c. Shell-side fluid pH [4 to 0 or 10 to 14]
- d. Shell-side gas H₂SO₄ partial pressure [0.15 to 75 psi]
- e. Shell-side gas CO₂ partial pressure [1.5 to 150 psi]

Related Factors:
- a. Shell-side fluid viscosity [100 to 700 SSU]
- b. Tube-side fluid viscosity [100 to 700 SSU]
- c. Shell-side gas density [0.1 to 0.5 lb/ft³]

E. Corroded Exchanger and Kettle Surfaces.

Critical Factors:
- a. Tube-side fluid pH [4 to 0 or 10 to 14]
- b. Shell-side fluid pH [4 to 0 or 10 to 14]
- c. Shell-side gas H₂SO₄ partial pressure [0.15 to 75 psi]
- d. Shell-side gas CO₂ partial pressure [1.5 to 150 psi]

Important Factors:
- a. Shell-side liquid cross flow velocity [7 to 13 ft/s]
- b. Atmospheric humidity [80 to 100%]

Related Factors:
- a. Shell-side fluid viscosity [100 to 500 SSU]
b. Tube-side fluid viscosity [100 to 500 SSU]
c. Shell-side gas density [0.1 to 0.5 lb/ft³]

MULTISTAGE COMPRESSOR  Ref. [16, 27, 29, 53, 61, 83]

A. Deformed Thrust Bearings.
Critical Factors:
a. Loads on thrust bearings [150 to 500 psi]
Important Factors:
a. Rotor speed [3000 to 20000 rpm]
Related Factors:
a. Atmospheric humidity [60 to 100%]

B. Plugged Stationary Elements.
Critical Factors:
a. Abrasive substances in gas [0.01 to 20 grains/ft³]
Important Factors:
a. Gas H₂SO₄ partial pressure [0.15 to 75 psia]
b. Gas CO₂ partial pressure [1.5 to 150 psia]
Related Factors:
a. Gas density [0.1 to 0.6 lb/ft³]

C. Eroded Impellers Exit Tips.
Critical Factors:
a. Abrasive substances in gas [0.05 to 10 grains/ft³]
Important Factors:
a. Inlet capacity [25000 to 30000 ft³]
b. Rotor speed [3000 to 20000 rpm]
Related Factors:
a. Gas density [0.15 to 0.7 lb/ft³]

D. Damaged Shaft and Interstage (Labyrinth) Seals.
Critical Factors:
a. Gas temperature [200 to 500 °F]
Important Factors:
a. Abrasive substances in gas [0.01 to 20 grains/ft³]
b. Discharge pressure [10 to 20 psi]
Related Factors:
a. Gas density [0.08 to 0.5 lb/ft³]
b. Atmospheric humidity [60 to 100%]

E. Misaligned Shaft.
Critical Factors:
a. Rotor speed [3000 to 10000 rpm]
Important Factors:
   a. Gas temperature [300 to 600 °F]

Related Factors:
   a. Gas density [0.15 to 0.7 lb/ft³]
   b. Atmospheric humidity [80 to 100%]

**PIPE (low pressure gas)** Ref. [28, 70, 73, 94, 103]

**A. Leaking Fittings or Joints.**
   Critical Factors:
   a. Gas pressure [250 to 500 psi]
   b. Gas temperature [400 to 750 °F]
   Important Factors:
   a. Abrasive substances in gas [0.8 to 15 grains/ft³]
   b. Gas H₂SO₄ partial pressure [0.15 to 75 psia]
   c. Gas CO₂ partial pressure [1.5 to 150 psia]
   Related Factors:
   a. Gas density [0.15 to 0.6 lb/ft³]

**B. Cracked Pipe Due To Over-stress.**
   Critical Factors:
   a. Pressure surges between 30 to 50% of MAOP (maximum allowable operating pressure)
   Important Factors:
   a. Gas pressure [200 to 500 psi]
   b. Gas temperature [400 to 500 °F]
   Related Factors:
   a. Gas H₂SO₄ partial pressure [0.15 to 75 psia]
   b. Gas CO₂ partial pressure [1.5 to 150 psia]

**C. Plugged Inner Section.**
   a. Abrasive substances in gas [0.8 to 15 grains/ft³]
   Important Factors:
   a. Gas temperature [200 to 500 °F]
   b. Gas H₂SO₄ partial pressure [0.15 to 75 psia]
   c. Gas CO₂ partial pressure [1.5 to 150 psia]
   Related Factors:
   a. Gas density [0.15 to 0.6 lb/ft³]

**D. Bent Pipe.**
   Critical Factors:
   a. Average span between supports [10 to 17 ft]
   b. Gas temperature [350 to 600 °F or -10 to -20 °F]
   Important Factors:
   a. Gas pressure [350 to 600 psi]
Related Factors:
a. Abrasive substances in gas [0.8 to 15 grains/ft³]

E. Corroded or Eroded Inner Wall.
Critical Factors:
a. Gas H₂SO₄ partial pressure [0.15 to 75 psia]
b. Gas CO₂ partial pressure [1.5 to 150 psia]
Important Factors:
a. Abrasive substances in gas [0.8 to 15 grains/ft³]
b. Gas temperature [200 to 500 °F]
Related Factors:
a. Atmospheric humidity [70 to 100%]

PIPE (low pressure fluid) Ref. [28, 70, 73, 94, 103]

A. Leaking Fittings or Joints.
Critical Factors:
a. Fluid pressure [250 to 500 psi]
b. Fluid temperature [400 to 750 °F]
Important Factors:
a. Abrasive substances in fluid [3 to 10% solids by weight]
b. Fluid pH [4 to 0 or 10 to 14]
Related Factors:
a. Fluid viscosity [500 to 3000 SSU]

B. Cracked Pipe Due To Over-stress.
Critical Factors:
a. Pressure surges between 10 to 20% of MAOP (maximum allowable operating pressure)
Important Factors:
a. Fluid pressure [100 to 150 psi]
b. Fluid temperature [300 to 450 °F]
c. Fluid cross flow velocity [12 to 22 ft/s]
Related Factors:
a. Fluid pH [4 to 0 or 10 to 14]

C. Plugged Inner Section.
a. Abrasive substances in fluid [5 to 10% solids by weight]
Important Factors:
a. Fluid temperature [150 to 300 °F]
b. Fluid pH [4 to 0 or 10 to 14]
c. Low fluid cross flow velocity [8 to 3 ft/s]
Related Factors:
a. Fluid viscosity [800 to 3500 SSU]
D. Bent Pipe.
Critical Factors:
- Average span between supports [8 to 14 ft]
- Gas temperature [350 to 600 °F or -20 to -30 °F]

Important Factors:
- Fluid pressure [100 to 200 psi]

Related Factors:
- Abrasive substances in fluid [5 to 10% solids by weight]

E. Corroded or Eroded Inner Wall.
Critical Factors:
- Fluid pH [4 to 0 or 10 to 14]

Important Factors:
- Abrasive substances in fluid [5 to 15% solids by weight]
- Fluid temperature [100 to 400 °F]
- Fluid cross flow velocity [10 to 20 ft/s]

Related Factors:
- Atmospheric humidity [70 to 100%]

REACTOR Ref. [7, 64, 65, 96, 101, 111]

A. Worn or Faulty Stirrer Couplings.
Critical Factors:
- Reaction temperature [200 to 800 °F]

Important Factors:
- Mixture viscosity [500 to 3000 SSU]
- Stirrer velocity [50 to 100 rpm]

Related Factors:
- Solution pH [4 to 0 or 10 to 14]

B. Non-lubricated Drive Bearings and Gears.
Critical Factors:
- Atmospheric humidity [60 to 100%]

Important Factors:
- Reaction temperature [150 to 700 °F]

Related Factors:
- Stirrer velocity [60 to 100 rpm]

C. Damaged Discharged Nozzle Seals.
Critical Factors:
- Reaction temperature [200 to 600 °F]

Important Factors:
- Vessel pressure [14.7 to 29.4 psi]

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Related Factors:
a. Mixture viscosity [300 to 2500 SSU]

D. Defective Heating Coils.
Important Factors:
a. Atmospheric humidity [80 to 100%]
b. Reaction temperature [200 to 700 °F]

WASTE HEAT BOILER Ref. [2, 9, 16, 45, 63, 78, 109]

A. Broken Expansion Joints.
Critical Factors:
a. Heating medium temperature [300 to 800 °F]

Important Factors:
a. Kettle pressure [50 to 150 psig]
b. Low heating medium cross-flow velocity [10 to 3 ft/s]

Related Factors:
a. Abrasive substances in kettle water [1 to 10% solids by weight]

B. Fouled Tubes.
Critical Factors:
a. Abrasive substances in kettle water [2 to 10% solids by weight]
b. Abrasive substances in heating medium [2 to 10% solids by weight]

Important Factors:
a. Heating medium temperature [200 to 800 °F]
b. Low heating medium cross-flow velocity [15 to 3 ft/s]
c. Heating medium and “water” pH [4 to 0 or 10 to 14]

Related Factors:
a. Heating medium viscosity [200 to 1000 SSU]
b. Kettle pressure [80 to 150 psig]

C. Deformed Demister Mesh Pad.
Critical Factors:
a. Steam pressure [50 to 150 psi]

Important Factors:
a. Kettle temperature [100 to 400 °F]

Related Factors:
a. Kettle “water” pH [4 to 0 or 10 to 14]

D. Cracked Boiler Drum Shell.
Critical Factors:
a. Kettle temperature [250 to 800 °F]
b. Kettle pressure [100 to 150 psig]
Important Factors:
a. Abrasive substances in water [1 to 8% solids by weight]

Related Factors:
a. Kettle “water” pH [4 to 0 or 10 to 14]
APPENDIX D

FAILURE MODES LOCAL AND PRODUCT EFFECTS

The information included in this appendix was obtained by series of interviews conducted with doctoral students of the department of Chemical Engineering at the University of Alabama. Specialized equipment maintenance literature (see references) was also consulted.

BURNER  Ref. [9, 21, 23, 24, 25, 53, 63, 86, 108]

A. Obstructed Inlet or Outlet Ducts of Blower.
   Local Effects: 3
   Product Effects: 3

B. Cracked Inlet Box of Blower.
   Local Effects: 3
   Product Effects: 4

C. Misaligned Wheel Bearings of Blower.
   Local Effects: 3
   Product Effects: 2

D. Cracked Wheel of Blower.
   Local Effects: 4
   Product Effects: 3

E. Damaged Shaft Seals of Blower.
   Local Effects: 2
   Product Effects: 3

F. Expanded Shaft of Blower.
   Local Effects: 3
   Product Effects: 4

G. Worn Wheel Blades of Blower.
   Local Effects: 2
   Product Effects: 2
H. Misaligned Couplings Inlet Bells of Blower.
   Local Effects: 3
   Product Effects: 2

I. Worn Scroll and Housing Liners of Blower.
   Local Effects: 4
   Product Effects: 3

J. Damaged Mechanical Seals in Stuffing Box of Pump.
   Local Effects: 2
   Product Effects: 4

K. Worn Impeller of Pump.
   Local Effects: 2
   Product Effects: 3

L. Faulty Thrust Bearings of Pump.
   Local Effects: 4
   Product Effects: 3

M. Deformed Shaft of Pump.
   Local Effects: 4
   Product Effects: 4

N. Leaking Casing of Pump.
   Local Effects: 2
   Product Effects: 3

O. Faulty Shaft Couplings of Pump.
   Local Effects: 4
   Product Effects: 4

P. Faulty Impeller Wear Ring of Pump.
   Local Effects: 4
   Product Effects: 2

Q. Plugged Spray Nozzle in Combustion Chamber.
   Local Effects: 2
   Product Effects: 2

R. Carbonaceous Matter Formation in Combustion Chamber.
   Local Effects: 2
   Product Effects: 1
CENTRIFUGAL BLOWER  Ref. [10, 16, 77, 53, 64, 78]

A. Obstructed Inlet or Outlet Ducts.
   Local Effects: 3
   Product Effects: 2

B. Cracked Inlet Box.
   Local Effects: 3
   Product Effects: 3

C. Misaligned Wheel Bearings.
   Local Effects: 3
   Product Effects: 2

D. Cracked Wheel.
   Local Effects: 4
   Product Effects: 2

E. Damaged Shaft Seals.
   Local Effects: 2
   Product Effects: 2

F. Expanded Shaft.
   Local Effects: 3
   Product Effects: 3

G. Worn Wheel Blades.
   Local Effects: 2
   Product Effects: 1

H. Misaligned Couplings Inlet Bells.
   Local Effects: 3
   Product Effects: 2

I. Worn Scroll and Housing Liners.
   Local Effects: 3
   Product Effects: 2

CENTRIFUGAL PUMP  Ref. [8, 15, 41, 42, 74, 86, 89, 108]

A. Damaged Mechanical Seals in Stuffing Box.
   Local Effects: 2
   Product Effects: 3
B. Worn Impeller
   Local Effects: 2
   Product Effects: 2

C. Faulty Thrust Bearings.
   Local Effects: 4
   Product Effects: 2

D. Deformed Shaft.
   Local Effects: 4
   Product Effects: 3

E. Leaking Casing.
   Local Effects: 2
   Product Effects: 2

F. Faulty Shaft Couplings.
   Local Effects: 4
   Product Effects: 3

G. Faulty Impeller Wear Ring.
   Local Effects: 4
   Product Effects: 2

CONVERTER Ref. [21, 23, 45, 51, 63, 64]

A. Damaged Supporting Grids.
   Local Effects: 2
   Product Effects: 3

B. Corroded or Cracked Supporting Flanges.
   Local Effects: 3
   Product Effects: 1

C. Plugged Vessel Walls and Ducts.
   Local Effects: 2
   Product Effects: 2

D. Fouled Heat Exchanger Tubes.
   Local Effects: 4
   Product Effects: 4
DISTILLATION TOWER Ref. [1, 9, 16, 21, 45, 53, 63, 75]

A. Deformed or Broken Rings.
   Local Effects: 3
   Product Effects: 3

B. Unleveled Liquid Distributor.
   Local Effects: 2
   Product Effects: 1

C. Plugged or Corroded Distributor.
   Local Effects: 2
   Product Effects: 2

D. Fouled Column Packing or Internals.
   Local Effects: 3
   Product Effects: 4

EVAPORATOR Ref. [5, 63, 64, 68, 81, 90, 108]

A. Damaged Mechanical Seals in Stuffing Box of Pump.
   Local Effects: 3
   Product Effects: 3

B. Worn Impeller of Pump.
   Local Effects: 3
   Product Effects: 3

C. Faulty Thrust Bearings of Pump.
   Local Effects: 4
   Product Effects: 3

D. Deformed Shaft of Pump.
   Local Effects: 4
   Product Effects: 3

E. Leaking Casing of Pump.
   Local Effects: 3
   Product Effects: 2

F. Faulty Shaft Couplings of Pump.
   Local Effects: 4
   Product Effects: 4
G. Faulty Impeller Wear Ring of Pump.
   Local Effects: 4
   Product Effects: 2

H. Broken Tube Support Baffles of Heat Exchanger.
   Local Effects: 4
   Product Effects: 3

I. Cracked Tubes of Heat Exchanger.
   Local Effects: 4
   Product Effects: 4

J. Deformed Impingement Plate of Heat Exchanger.
   Local Effects: 1
   Product Effects: 1

K. Fouled Tubes of Heat Exchanger.
   Local Effects: 4
   Product Effects: 3

L. Corroded Exchanger and Kettle Surfaces.
   Local Effects: 2
   Product Effects: 2

M. Plugged or Corroded Vapor Heads Walls.
   Local Effects: 1
   Product Effects: 2

N. Leaking Circulation Pipe Joints.
   Local Effects: 3
   Product Effects: 3

O. Plugged Tube Inlets.
   Local Effects: 2
   Product Effects: 3

HEAT EXCHANGER  Ref. [16, 27, 29, 53, 61, 83]

A. Broken Tube Support Baffles.
   Local Effects: 4
   Product Effects: 3
B. Cracked Tubes.
Local Effects: 4
Product Effects: 4

C. Deformed Impingement Plate.
Local Effects: 1
Product Effects: 1

D. Fouled Tubes.
Local Effects: 4
Product Effects: 3

E. Corroded Exchanger and Kettle Surfaces.
Local Effects: 2
Product Effects: 2

MULTISTAGE COMPRESSOR Ref. [16, 27, 29, 53, 61, 83]

A. Deformed Thrust Bearings.
Local Effects: 3
Product Effects: 4

B. Plugged Stationary Elements.
Local Effects: 3
Product Effects: 3

C. Eroded Impellers Exit Tips.
Local Effects: 2
Product Effects: 2

D. Damaged Shaft and Interstage (Labyrinth) Seals.
Local Effects: 3
Product Effects: 3

E. Misaligned Shaft.
Local Effects: 4
Product Effects: 3

PIPE Ref. [28, 70, 73, 94, 103]

A. Leaking Fittings or Joints.
Local Effects: 1
Product Effects: 3

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B. Cracked Pipe Due To Over-stress.
   Local Effects: 1
   Product Effects: 3

C. Plugged Inner Section.
   Local Effects: 2
   Product Effects: 3

D. Bent Pipe.
   Local Effects: 2
   Product Effects: 2

E. Corroded or Eroded Inner Wall.
   Local Effects: 2
   Product Effects: 2

REACTOR Ref. [7, 64, 65, 96, 101, 111]

A. Worn or faulty Stirrer Couplings.
   Local Effects: 2
   Product Effects: 2

B. Non-lubricated Drive Bearings and Gears.
   Local Effects: 3
   Product Effects: 2

C. Damaged Discharged Nozzle Seals.
   Local Effects: 2
   Product Effects: 3

D. Defective Heating Coils.
   Local Effects: 2
   Product Effects: 3

WASTE HEAT BOILER Ref. [2, 9, 16, 45, 63, 78, 109]

A. Broken Expansion Joints.
   Local Effects: 3
   Product Effects: 3

B. Fouled Tubes.
   Local Effects: 3
   Product Effects: 3
C. Deformed Demister Mesh Pad.
  Local Effects: 1
  Product Effects: 2

D. Cracked Boiler Drum Shell.
  Local Effects: 4
  Product Effects: 4
APPENDIX E

FAILURE MODES NMS, DMS, NES, AND DES VALUES

The NMS, DMS, NES, and DES values depicted in this appendix were obtained by series of interviews conducted with doctoral students of the department of Chemical Engineering at the University of Alabama. Specialized equipment maintenance literature (see references) was also consulted.

BURNER  Ref. [9, 21, 23, 24, 25, 53, 63, 86, 108]

A. Obstructed Inlet or Outlet Ducts of Blower.
NMS = 0.25
DMS = 0.00  \textbf{not pipe transmitted}

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B. Cracked Inlet Box of Blower.
NMS = 0.25
DMS = 0.00  \textbf{not pipe transmitted}

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Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Reactor 0.00 0.00
Waste Heat Boiler 0.00 0.00

C. Misaligned Wheel Bearings of Blower.
NMS = 0.50
DMS = 0.00 **not pipe transmitted**

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D. Cracked Wheel of Blower.
NMS = 0.25
DMS = 0.00 **not pipe transmitted**

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E. Damaged Shaft Seals of Blower.
NMS = 0.25
DMS = 0.00 **not pipe transmitted**

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**F. Expanded Shaft of Blower.**
NMS = 0.50
DMS = 0.00  **not pipe transmitted**

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**G. Worn Wheel Blades of Blower.**
NMS = 0.00
DMS = 0.00  **not pipe transmitted**

**H. Misaligned Couplings Inlet Bells of Blower.**
NMS = 0.25
DMS = 0.00  **not pipe transmitted**

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**I. Worn Scroll and Housing Liners of Blower.**
NMS = 0.50
DMS = 0.00  **not pipe transmitted**

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Multistage Compressor 0.25 0.00
Pipe 0.00 0.00
Reactor 0.00 0.00
Waste Heat Boiler 0.00 0.00

**J. Damaged Mechanical Seals in Stuffing Box of Pump.**

NMS = 0.25
DMS = 0.00  **not pipe transmitted**

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**K. Worn Impeller of Pump.**

NMS = 0.25
DMS = 0.00  **not pipe transmitted**

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**L. Faulty Thrust Bearings of Pump.**

NMS = 0.75
DMS = 0.00  **not pipe transmitted**

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**M. Deformed Shaft of Pump.**
NMS = 0.50
DMS = 0.00  **not pipe transmitted**

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**N. Leaking Casing of Pump.**
NMS = 0.00
DMS = 0.00  **not pipe transmitted**

**O. Faulty Shaft Couplings of Pump.**
NMS = 0.50
DMS = 0.00  **not pipe transmitted**

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<tr>
<td>Waste Heat Boiler</td>
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**P. Faulty Impeller Wear Ring of Pump.**
NMS = 0.00
DMS = 0.25  **pipe transmitted**
Q. Plugged Spray Nozzle in Combustion Chamber.
NMS = 0.00
DMS = 0.00  not pipe transmitted

R. Carbonaceous Matter Formation in Combustion Chamber.
NMS = 0.00
DMS = 0.00  not pipe transmitted

CENTRIFUGAL BLOWER Ref. [10, 16, 77, 53, 64, 78]

A. Obstructed Inlet or Outlet Ducts.
NMS = 0.25
DMS = 0.00  not pipe transmitted

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<td>Waste Heat Boiler</td>
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B. Cracked Inlet Box.
NMS = 0.25
DMS = 0.00  not pipe transmitted

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Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
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**C. Misaligned Wheel Bearings.**

NMS = 0.50
DMS = 0.00  **not pipe transmitted**

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**D. Cracked Wheel.**

NMS = 0.25
DMS = 0.00  **not pipe transmitted**

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**E. Damaged Shaft Seals.**

NMS = 0.25
DMS = 0.00  **not pipe transmitted**

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**F. Expanded Shaft.**

NMS = 0.50
DMS = 0.00  **not pipe transmitted**

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**G. Worn Wheel Blades.**

NMS = 0.00
DMS = 0.00  **not pipe transmitted**

**H. Misaligned Couplings Inlet Bells.**

NMS = 0.25
DMS = 0.00  **not pipe transmitted**

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**I. Worn Scroll and Housing Liners.**

NMS = 0.50
DMS = 0.75  **pipe transmitted**
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**CENTRIFUGAL PUMP** Ref. [8, 15, 41, 42, 74, 86, 89, 108]

**A. Damaged Mechanical Seals in Stuffing Box.**

NMS = 0.25  
DMS = 0.00  
*not pipe transmitted*

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**B. Worn Impeller**

NMS = 0.25  
DMS = 0.00  
*not pipe transmitted*

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C. Faulty Thrust Bearings.
NMS = 0.75
DMS = 0.00  **not pipe transmitted**

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D. Deformed Shaft.
NMS = 0.50
DMS = 0.00  **not pipe transmitted**

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E. Leaking Casing.
NMS = 0.00
DMS = 0.00  **not pipe transmitted**

F. Faulty Shaft Couplings.
NMS = 0.50
DMS = 0.00  **not pipe transmitted**

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Pipe                      0.00  0.00  
Reactor                   0.25  0.00  
Waste Heat Boiler         0.25  0.00  

G. Faulty Impeller Wear Ring.  
NMS = 0.00  
DMS = 0.25  **pipe transmitted**  
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<td>0.25</td>
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CONVERTER  Ref. [21, 23, 45, 51, 63, 64]

A. Damaged Supporting Grids.  
NMS = 0.00  
DMS = 0.00  **not pipe transmitted**  

B. Corroded or Cracked Supporting Flanges.  
NMS = 0.00  
DMS = 0.00  **not pipe transmitted**  

C. Plugged Vessel Walls and Ducts.  
NMS = 0.00  
DMS = 0.25  **pipe transmitted**  
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<tr>
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<th>DES</th>
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<tbody>
<tr>
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</tr>
<tr>
<td>Evaporator</td>
<td>0.00</td>
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<tr>
<td>Heat Exchanger</td>
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<tr>
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<tr>
<td>Waste Heat Boiler</td>
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### D. Fouled Heat Exchanger Tubes.

NMS = 0.00  
DMS = 0.75  **not pipe transmitted**

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### A. Deformed or Broken Rings.

NMS = 0.00  
DMS = 1.00  **pipe transmitted**

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<td>Converter</td>
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### B. Unleveled Liquid Distributor.

NMS = 0.00  
DMS = 0.00  **not pipe transmitted**

### C. Plugged or Corroded Distributor.

NMS = 0.00  
DMS = 0.50  **pipe transmitted**

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**DISTILLATION TOWER** Ref. [1, 9, 16, 21, 45, 53, 63, 75]

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D. Fouled Column Packing or Internals.
NMS = 0.50
DMS = 0.50  **not pipe transmitted**

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<tr>
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**EVAPORATOR** Ref. [5, 63, 64, 68, 81, 90, 108]

A. Damaged Mechanical Seals in Stuffing Box of Pump.
NMS = 0.25
DMS = 0.00  **not pipe transmitted**

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B. Worn Impeller of Pump
NMS = 0.25
DMS = 0.00  **not pipe transmitted**

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</table>
Centrifugal Blower  0.00  0.00  
Converter  0.00  0.00  
Distillation Tower  0.25  0.00  
Centrifugal Pump  0.25  0.00  
Heat Exchanger  0.25  0.00  
Multistage Compressor  0.25  0.00  
Pipe  0.00  0.00  
Reactor  0.25  0.00  
Waste Heat Boiler  0.25  0.00  

C. Faulty Thrust Bearings of Pump.  
NMS = 0.75  
DMS = 0.00  **not pipe transmitted**  
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D. Deformed Shaft of Pump.  
NMS = 0.50  
DMS = 0.00  **not pipe transmitted**  
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E. Leaking Casing of Pump.  
NMS = 0.00  
DMS = 0.00  **not pipe transmitted**
### F. Faulty Shaft Couplings of Pump.

NMS = 0.50  
DMS = 0.00  **not pipe transmitted**

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### G. Faulty Impeller Wear Ring of Pump.

NMS = 0.00  
DMS = 0.25  **pipe transmitted**

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### H. Broken Tube Support Baffles of Heat Exchanger.

NMS = 0.00  
DMS = 0.00  **not pipe transmitted**

### I. Cracked Tubes of Heat Exchanger.

NMS = 0.00  
DMS = 0.25  **pipe transmitted**

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**J. Deformed Impingement Plate of Heat Exchanger**

NMS = 0.00  
DMS = 0.00 not pipe transmitted

**K. Fouled Tubes of Heat Exchanger.**

NMS = 0.00  
DMS = 0.25 pipe transmitted

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**L. Corroded Exchanger and Kettle Surfaces.**

NMS = 0.00  
DMS = 0.25 pipe transmitted

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</table>

**M. Plugged or Corroded Vapor Heads Walls.**

NMS = 0.00  
DMS = 0.00 not pipe transmitted

**N. Leaking Circulation Pipe Joints.**

NMS = 0.00  
DMS = 0.25 pipe transmitted
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**O. Plugged Tube Inlets.**

NMS = 0.00

DMS = 0.25  **pipe transmitted**

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<td>Centrifugal Pump</td>
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<tr>
<td>Converter</td>
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<tr>
<td>Multistage Compressor</td>
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<tr>
<td>Pipe</td>
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<tr>
<td>Reactor</td>
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<tr>
<td>Waste Heat Boiler</td>
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</tbody>
</table>

**HEAT EXCHANGER** Ref. [16, 27, 29, 53, 61, 83]

**A. Broken Tube Support Baffles.**

NMS = 0.00

DMS = 0.25  **pipe transmitted**

<table>
<thead>
<tr>
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<tr>
<td>Waste Heat Boiler</td>
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</table>
### B. Cracked Tubes.
NMS = 0.00
DMS = 0.25  **pipe transmitted**

<table>
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</tr>
<tr>
<td>Waste Heat Boiler</td>
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</tbody>
</table>

### C. Deformed Impingement Plate.
NMS = 0.00
DMS = 0.00  **pipe transmitted**

### D. Fouled Tubes.
NMS = 0.00
DMS = 0.25  **pipe transmitted**

<table>
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<td>Pipe</td>
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<tr>
<td>Reactor</td>
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</tr>
<tr>
<td>Waste Heat Boiler</td>
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### E. Corroded Exchanger and Kettle Surfaces.
NMS = 0.00
DMS = 0.25  **pipe transmitted**

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<tr>
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<td>Evaporator</td>
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</tr>
<tr>
<td>Multistage Compressor</td>
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</tbody>
</table>

204

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Pipe  
Reactor  
Waste Heat Boiler  

MULTISTAGE COMPRESSOR  Ref. [16, 27, 29, 53, 61, 83]

A. Deformed Thrust Bearings.
NMS = 0.00
DMS = 0.50  pipe transmitted

<table>
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<td>Converter</td>
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</tr>
<tr>
<td>Heat Exchanger</td>
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<td>Pipe</td>
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<tr>
<td>Reactor</td>
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<tr>
<td>Waste Heat Boiler</td>
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</table>

B. Plugged Stationary Elements.
NMS = 0.00
DMS = 0.25  pipe transmitted

<table>
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<tr>
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<tr>
<td>Waste Heat Boiler</td>
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</table>

C. Eroded Impellers Exit Tips.
NMS = 0.25
DMS = 0.25  pipe transmitted

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<td>Centrifugal Pump</td>
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<tr>
<td>Converter</td>
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205
Distillation Tower 0.00 0.00
Evaporator 0.00 0.00
Heat Exchanger 0.25 0.25
Pipe 0.00 0.00
Reactor 0.25 0.25
Waste Heat Boiler 0.00 0.00

D. Damaged Shaft and Interstage (Labyrinth) Seals.
NMS = 0.00
DMS = 0.25  pipe transmitted

<table>
<thead>
<tr>
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<tbody>
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<tr>
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<td>Centrifugal Pump</td>
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<td>Converter</td>
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</tr>
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<td>Heat Exchanger</td>
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<td>Pipe</td>
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<tr>
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<tr>
<td>Waste Heat Boiler</td>
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</table>

E. Misaligned Shaft.
NMS = 0.25
DMS = 0.25  pipe transmitted

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<th>NES</th>
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<td>Converter</td>
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<td>Distillation Tower</td>
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<td>Heat Exchanger</td>
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<td>Reactor</td>
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<tr>
<td>Waste Heat Boiler</td>
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</table>

PIPE  Ref. [28, 70, 73, 94, 103]

A. Leaking Fittings or Joints.
NMS = 0.00
DMS = 0.00
B. Cracked Pipe Due To Over-stress.
NMS = 0.00
DMS = 0.00

C. Plugged Inner Section.
NMS = 0.00
DMS = 0.00

D. Bent Pipe.
NMS = 0.00
DMS = 0.00

E. Corroded or Eroded Inner Wall.
NMS = 0.00
DMS = 0.00

REACTOR Ref. [7, 64, 65, 96, 101, 111]

A. Worn or faulty Stirrer Couplings.
NMS = 0.75
DMS = 0.00 not pipe transmitted

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<tr>
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<tr>
<td>Multistage Compressor</td>
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<td>Pipe</td>
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<tr>
<td>Waste Heat Boiler</td>
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</table>

B. Non-lubricated Drive Bearings and Gears.
NMS = 0.00
DMS = 0.00

C. Damaged Discharged Nozzle Seals.
NMS = 0.00
DMS = 0.50 not pipe transmitted

<table>
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</table>

WASTE HEAT BOILER  Ref. [2, 9, 16, 45, 63, 78, 109]

**A. Broken Expansion Joints.**
NMS = 0.00  
DMS = 0.00  
*not pipe transmitted*

**B. Fouled Tubes.**
NMS = 0.00  
DMS = 0.00  
*not pipe transmitted*

**C. Deformed Demister Mesh Pad.**
NMS = 0.00  
DMS = 0.00  
*not pipe transmitted*

**D. Cracked Boiler Drum Shell.**
NMS = 0.25  
DMS = 0.00  
*not pipe transmitted*
APPENDIX F
SYSTEM OUTPUT SAMPLE REPORT

************* RCM CHEMICAL PROCESS EXPERT SYSTEM *************

Project Name: SOLID.XLS

BLOWER_2
No specific failure mode is of concern for this machine

BURNER_2
No specific failure mode is of concern for this machine

COMPRESSOR
No specific failure mode is of concern for this machine

HEAT_2
No specific failure mode is of concern for this machine

PUMP
No specific failure mode is of concern for this machine

REACTOR
No specific failure mode is of concern for this machine

//////// CRITICAL FAILURE MODES //////////

Priority Index: 64 [ LI: 4, LEI: 4, PEI: 4, SFI: 1 ]

*CONVERTER <> Fouled Heat Exchanger Tubes.
  Local Effects:
  - Converter efficiency greatly reduced
  - Increase in internal gas temperature
  - Possible damage of flanges and support grids
  - Reaction heat out of control
  - Eventually, total loss of function

  System Effects:
  - Extremely high gas temperatures can damage circulating pipes and downstream machines' seals
  - If converter ceases working, the whole process will probably have to be shut down
Suggested Controls:
- Dye penetrant inspection
- Fluorescent (Zyglo) inspection
- Differential temperature control

Priority Index: 36 [ LI: 4, LEI: 3, PEI: 3, SFI: 1 ]
*BLOWER_1 * <Cracked Inlet Box.

Local Effects:
- Flow pressure loss
- Overloading of the fan motor
- Gas/air leakage
- Eventual loss of equipment's function

System Effects:
- If blower used for cooling, system components or product temperature will get out of control
- Electrical power supply to other equipment may be affected if blower motor overloads
- If handling gas, contamination hazard
- Possible corrosive effect on nearby equipment

Suggested Controls:
- Gas detector
- Visual inspection
- Dye penetrant inspection

*EVAPORATOR * <Plugged Tube Inlets.

Local Effects:
- Liquid contamination
- Possible fouling of heat exchanger tubes
- Evaporator efficiency greatly reduced

System Effects:
- Contamination hazard
- Clogged inlets may affect the normal operation of downstream pumps, compressors or distillation towers
- If evaporator ceases working, overall process may have to be shut down

Suggested Controls:
- Visual inspection
- Ultrasonic inspection

Priority Index: 24 [ LI: 4, LEI: 3, PEI: 2, SFI: 1 ]
*BLOWER_1 * <Misaligned Wheel Bearings.

Local Effects:
- Motor overloaded
- Possible bending of shaft
- Extreme equipment vibration and noise
- Blowing power loss

System Effects:
- If blower used for cooling, system components or product temperature may get out of control
- Electrical power supply to other equipment may be affected if blower motor overloads
- Nearby equipment may be atrophied due to transmitted vibration

Suggested Control:
- Mechanical running test
- Visual inspection
- Vibration analysis
- Rotor stability test

Priority Index: 24 [ LI: 4, LEI: 3, PEI: 2, SFI: 1]

*BLOWER_1 Misaligned Couplings Inlet Bells.

Local Effects:
- Overheating of bearings and motor
- Bearing failure
- Increase of bearing dust seals wear

System Effects:
- Electrical power supply to other equipment may be affected if blower motor overloads

Suggested Controls:
- Temperature detectors (thermocouples & electrical resistance detectors)
- Mechanical test
- Visual inspection

Priority Index: 17.5 [ LI: 4, LEI: 2, PEI: 2, SFI: 1.09375]

*EVAPORATOR Corroded Exchanger and Kettle Surfaces.

Local Effects:
- Apparatus efficiency greatly reduced
- Liquid contamination
- Liquid evaporation efficiency reduced

System Effects:
- Process temperature may go out of control
- Kettle scum may atrophy attached pipes and pumps

Suggested Controls:
- Visual inspection
- Eddy current inspection

Priority Index: 24 [ LI: 4, LEI: 3, PEI: 2, SFI: 1]

*BLOWER_1 Misaligned Couplings Inlet Bells.

Local Effects:
- Overheating of bearings and motor
- Bearing failure
- Increase of bearing dust seals wear

System Effects:
- Electrical power supply to other equipment may be affected if blower motor overloads

Suggested Controls:
- Temperature detectors (thermocouples & electrical resistance detectors)
- Mechanical test
- Visual inspection

Priority Index: 17.5 [ LI: 4, LEI: 2, PEI: 2, SFI: 1.09375]
*DIST_TW4  <>Plugged or Corroded Distributor.

Local Effects:
- Fluid contamination
- Reduced tower efficiency
- Poor liquid distribution
- Possible inappropriate column flooding

System Effects:
- Poor distillate quality
- Pumps or compressors handling distillate may be slightly affected

Suggested Controls:
- Visual inspection
- Column differential pressure analysis

*BLOWER_1  <>Damaged Shaft Seals.

Local Effects:
- Gas/air leakage around shaft
- Loss of blower pressure and efficiency
- Possible corrosion of other elements

System Effects:
- If blower used for cooling, system components or product temperature will get out of control
- Electrical power supply to other equipment may be affected if blower motor overloads
- If handling gas, contamination hazard
- Possible corrosive effect on nearby equipment

Suggested Controls:
- Static gas test
- Visual inspection
- Temperature detectors (thermocouples & electrical resistance detectors)

*PIPE  <>Corroded or Eroded Inner Wall.

Local Effects:
- Development of "hot spots" on piping wall
- Eventual pipe fracture
- Fluid contamination

System Effects:
- Contaminated fluid may affect the normal functioning of downstream machinery
Suggested Controls:
- Ultrasonic inspection
- Eddy current inspection

Priority Index: 11.86798493 [ LI:1.31866499, LEI:3, PEI:3, SFI:1]
*BOILER <> Fouled Tubes.
Local Effects:
- Heating medium leakage into boiling water
- Substance contamination
- Equipment efficiency greatly reduced
System Effects:
- Product quality greatly affected
- If water is circulated, major equipment damage and contamination should be expected in nearby areas
- Heating sub-system components may get wrecked
Suggested Controls:
- Ultrasonic inspection
- Differential temperature analysis
- Magnetic particle inspection
- Eddy current inspection

Priority Index: 8 [ LI:4, LEI:1, PEI:2, SFI:1]
*EVAPORATOR <> Plugged or Corroded Vapor Heads Walls.
Local Effects:
- Vapor entrainment
- Loss of evaporation efficiency
System Effects:
- Attached vents and ducts can be damaged
- No major effects on process should be expected
Suggested Controls:
- Visual inspection
- Ultrasonic inspection
APPENDIX G

VALIDATION RESULTS

This appendix contains the main comments expressed by the experts after evaluating the results generated by the program during the validation phase. The comments are sorted by operation unit.

BURNER
The vast majority (85%) of the failure modes in the final RCM reports are frequently encountered in industrial settings. The atomizing air rate should have a larger contribution to the final failure mode screening. Failure modes associated with the combustion chamber do not appear in the system’s final report as frequently as expected.

CENTRIFUGAL BLOWER
Although the system was very efficient detecting common failure modes for centrifugal blowers, there were two, worn scroll and cracked inlet box, that rarely appeared in the RCM analysis.

CENTRIFUGAL PUMP
This was one of the equipment units where the performance of the system was at its best. Basically, all expected failure modes were properly detected and prioritized by the expert system.

CONVERTER
Failure modes associated to the catalyst properties (weight, pH, etc.) were rarely presented in the system’s final reports. All other failure modes were detected as expected.

DISTILLATION TOWER
This should be renamed as “packed tower” since the system allows the user to employ it as an absorbing or stripping unit. The impact of the liquid feed rate on the final results was not as expected. All other factors were properly considered by the logic embedded in the program.
**EVAPORATOR**
All generated RCM analyses during the validation process yielded the expected results. More failure modes for the vapor head component should be included in the knowledge base.

**HEAT EXCHANGER**
The solutions obtained when liquid was assumed as tube-side substance were more satisfactory than for the cases where gas was adopted as tube-side substance. This may be a result of the way in which the system handles the gas density property when screening the failure modes.

**MULTISTAGE COMPRESSOR**
All expected failure modes were correctly considered by the system during the validation trials. However, the failure mode “plugged stationary elements” appeared in the final reports twice as much as expected.

**PIPELINE**
All the system’s reports regarding gas and liquid pipelines were consistent with what was expected.

**REACTOR**
More safety-related failure modes should be considered by the system. Also, failure modes related to the reactor shaft should appear more in the system’s conclusion as it was noticed in the validation process.

**WASTE HEAT BOILER**
A more precise parameter than the water pH should be used for accessing the effects of “hard water” in the kettle walls of the apparatus. Nevertheless, the analyses given by the system were very satisfactory, and consistent with what was expected.
Daniel J. Fonseca was born in 1969 in San Jose, Costa Rica. He received a bachelor of science and a master of science degrees in Industrial Engineering from the University of Alabama, and a master of science degree in Engineering Science from Louisiana State University in 1997.

Prior to attending L.S.U., Mr. Fonseca was as an assistant professor in the Department of Industrial Engineering, at the Monterrey Institute of Technology in Mexico City, where he was involved with the design and improvement of manufacturing and services systems in medium to large scale companies. He also served as Industrial Products Sales Manager for Kimberly Clark of Costa Rica. In May of 1998 he will receive the degree of Doctor of Philosophy.
DOCTORAL EXAMINATION AND DISSERTATION REPORT

Candidate: Daniel J. Fonseca

Major Field: Engineering Science

Title of Dissertation: A Knowledge Based System for Reliability Centered Maintenance in the Chemical Industry

Approved:

[Signatures]

Major Professor and Chairman
Dean of the Graduate School

EXAMINING COMMITTEE:

[Signatures]

Date of Examination:

2/27/98