An Introduction to
Advanced Diagnostics and Prognostics
For NRC Staff

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Prepared by
SoHaR Incorporated
Culver City, California

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Foreword

The term "advanced diagnostics and prognostics" (AD&P) generally refers to the application of automated monitoring, incipient failure detection, condition assessment, and prognosis. Properly designed and implemented AD&P technologies could be beneficial for safe and reliable operation of nuclear power plant (NPP) and nuclear fuel cycle facilities (NFCFs). The goal of this research project was to prepare information for reviewing and evaluating licensing applications that propose to integrate AD&P into NPPs and NFCFs in the United States.

This report surveys the technical and regulatory landscape with respect to AD&P techniques and methodologies. It is presented in two parts. Part 1 provides a general review of AD&P techniques and methodologies. Part 2 identifies regulations, regulatory guidance, and standards that may impact AD&P designs and implementations for NPP and NFCF applications.

Part 1 is intended to provide a general understanding of the types of AD&P technologies that are available or may become available in the near future. The discussion does not constitute a comprehensive listing of AD&P technologies and methodologies. Example implementations are provided to highlight how AD&P methodologies have been implemented and the types of technical questions that might arise in reviewing an AD&P implementation in an NPP or NFCF.

The regulations, regulatory guidance, and standards discussed were also considered for purposes of providing an overview. No information was found to indicate that any existing regulations in the United States prohibit the safe use of AD&P in NPPs and NFCFs. Digital Instrumentation and Controls Interim Staff Guidance-4, however, states that functions that are not necessary for safety, even if they enhance reliability, should be executed outside of the safety system [Agencywide Documents Access and Management System Accession Number ML083310185]. No information was found to indicate that intensive AD&P processes need to be executed within safety systems. More research may be needed to determine if additional or changed requirements and guidance is needed for safe implementations of AD&P in NPPs and NFCFs.

This report may be useful to NRC staff as a basic knowledge reference on AD&P to support staff exercise of technical judgments during regulatory reviews of applications involving the use of AD&P technology.

Mauricio Gutierrez
Project Manager

Paul Rebstock
Technical Monitor

Russell Sydnor
Branch Chief

Instrumentation and Controls and Electrical Engineering Branch
Division of Engineering
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission.

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Executive Summary

This report on Advanced Diagnostics and Prognostics (AD&P) is composed of two parts. Part 1 provides a background to the current field of Advanced Diagnostics and Prognostics and discusses implementations that are currently available or are under development and are likely to be proposed for use in domestic nuclear facilities. The second part is concerned with regulatory considerations and focuses on existing regulations, regulatory guidance, and industry standards that may impact the application and use of AD&P in nuclear power plants and fuel cycle facilities.

The main difference between diagnostics and prognostics lies in their objective: The goal of diagnostics is to identify and isolate failed equipment, while the goal of prognostics (also termed predictive diagnostics) is to warn of impending failure, and when possible quantify the Remaining Useful Life (RUL) with a defined confidence level for a specified set of conditions.

The body of the report starts with an examination of the failure process; as part of this it is found that in many situations empirical criteria are used to define end of life of a component or system. An indication of an abnormal plant state can be due to either a failure of the plant or a failure of the instrumentation. Techniques for resolving this ambiguity are discussed. Maintenance is usually the largest expense item for nuclear power plants, and within this personnel cost are the largest component. AD&P holds promise for reducing maintenance labor and this will be an incentive for its adoption by plant operators.

A variety of AD&P techniques are introduced and their classification and maturity level are discussed. There are a few applications in non-safety areas of nuclear power plants that may become the starting point for their introduction into functions subject to license.

Part 2 of the report discusses statutory requirements that may affect the use of AD&P, regulatory guidance documents and pertinent industry standards. Self-test and built-in test are the only applications currently covered. If the regulatory environment for these and for another AD&P related area, remote monitoring, is taken as an example there will be few significant obstacles to future use of AD&P.

Important additional information is contained in two appendices:

Appendix A – Taxonomies: two taxonomies for classifying diagnostic and prognostic techniques as well as an annotated bibliography of diagnostic and prognostic techniques.

Appendix B – Resources for Additional Information: a listing of organizations and conferences dealing with diagnostics and prognostics

List of Abbreviations

AD&P	Advanced Diagnostics and Prognostics
ASME	American Society of Mechanical Engineers
AEC	Atomic Energy Commission
BIST	Built In Self-Test
BIT	Built In Test
CALCE	Center for Advanced Life Cycle Engineering
CDF	Core Damage Frequency
COTS	Commercial Off The Shelf
DOE	Department of Energy
EDAC	Error Detection and Correction
EOL	End Of Life
EOUL	End Of Useful Life
EPRI	Electric Power Research Institute, Inc.
IAEA	International Atomic Energy Agency
IASCC	Irradiation Assisted Stress Corrosion Cracking
I&C	Instrumentation and Control
ICFD	In-Core Flux Detector
IDP	Independent Decision-making Panel
IEEE	Institute of Electrical and Electronics Engineers
IGSCC	Inter-Granular Stress Corrosion Cracking
INPO	Institute of Nuclear Power Operations
IROFS	Items Relied On For Safety
IST	In Service Testing
ISG	Interim Staff Guidance
LER	Licensee Event Reports
LERF	Large Early Release Frequency
NEI	Nuclear Energy Institute
NFCF	Nuclear Fuel Cycle Facility
NPP	Nuclear Power Plant
NRC	U.S. Nuclear Regulatory Commission
OLM	Online Monitoring
O&M	Operation and Maintenance
OTS	Off-the-Shelf
PHM	Prognostics and Health Management
PRA	Probabilistic Risk Assessment
RG	Regulatory Guide
RI-IST	Risk Informed In Service Testing
RUL	Remaining Useful Life
SFCP	Surveillance Frequency Control Program
SR	Surveillance Requirements
SRP	Standard Review Plan (SRP)

SSC	Systems, Structures, Components
TS	Technical Specification
TSTF	Technical Specification Task Force
UUT	Unit Under Test
V&V	Validation and Verification

1 Introduction

This report on Advanced Diagnostics and Prognostics (AD&P) consists of two parts: Part 1 describes methods and techniques in current use or expected to be available in the foreseeable future, including but not restricted to Nuclear Power Plants (NPPs) or Nuclear Fuel Cycle Facilities (NFCFs). Part 2 deals with regulatory considerations relevant to the implementation of AD&P in NPPs and NFCFs.

The information and recommendations in this document are intended to help the NRC determine whether regulations, guidance, or Technical Specification provisions should be created or updated to address proposed uses of AD&P in domestic nuclear power plants. The NRC may also use the content in this document to determine if review procedures and acceptance criteria for the evaluation of proposed implementations of AD&P should be developed.

The field of diagnostics and prognostics of engineered equipment covers many engineering disciplines and has given birth to diverse technologies that are applied to the monitoring of different types of equipment. The technologies and methodologies sampled in this report were chosen because they are currently applicable or may become applicable to the nuclear field. The technologies and methodologies discussed do not constitute a comprehensive listing.

The main difference between diagnostics and prognostics lies in their objective: The goal of diagnostics is to identify and isolate failed equipment, while the goal of prognostics (also termed predictive diagnostics) is to warn of impending failure, and when possible quantify the Remaining Useful Life (RUL) with a defined confidence level for a specified set of conditions.[1]

Although implementations of specific methods for diagnostic goals are often much more mature than implementations directed towards prognostic goals, this report acknowledges the common physical and algorithmic roots by including them under the same umbrella. Where appropriate the maturity of diagnostic and prognostic techniques is assessed separately. In general, the field of prognostics is evolving with much research and experimentation but with few current implemented solutions in industry, and fewer yet that are reported for NPPs or NFCFs.

1.1 Purpose

The first part of this report presents an overview of the field of advanced diagnostics and prognostics along with a collection of representative methods. It discusses the goals and reasons for use of AD&P and the safety and cost ramifications of its use in nuclear facilities. For this purpose examples of AD&P

[1] Self-Test and Built In Test are internal implementations of prognostics and diagnostics.

techniques are presented and some are described in detail to show the reasons for their adoption as well as the many steps that were necessary for their development. Throughout this report generic assessment questions for AD&P methodologies are included to alert the reader to possible pitfalls in their implementation.

1.2 Definitions

The term "Advanced Diagnostics and Prognostics" (AD&P) refers generally to the application of automated monitoring, condition assessment, and incipient failure detection. It also includes self-testing of digital systems and calibration verification at digital system interfaces. In particular the term "advanced" is used here to include diagnostics and prognostics that will be employed in advanced nuclear power plants and fuel treatment facilities, and will often rely on sophisticated monitoring capabilities and requirements. The terms *diagnostics* and *prognostics* (D&P) are interpreted as the methodologies for performing diagnoses and prognoses, respectively. Therefore definitions of *diagnosis* and *prognosis* are also presented.

An early definition of Diagnosis as it is applied to *engineered equipment* can be found in MIL-STD 1309D (MIL-STD-1309D, 1992) clauses 3.1.161 and 3.1.166:

> *3.1.161 Diagnosis. The functions performed and the techniques used in determining and isolating the cause of malfunctions.*
>
> *3.1.166 Diagnostic test. A test performed for the purpose of isolating a malfunction in the Unit Under Test (UUT) or confirming that there actually is a malfunction.*

Advanced diagnostics will often rely on multiple tests and methods and may be applied to conditions that cannot be fully diagnosed by conventional methods. The multiplicity of tests and evidence raise it from a task to an engineering discipline or art. A definition that more accurately describes the current and future field of diagnostics is:

DEFINITION 1

> ***Diagnostics – The art of identifying and correlating the results of multiple tests to determine system condition and status and to generate the input required for optimal maintenance.***

According to the International Organization for Standardization, the term "failure prognostics" corresponds to the "estimation of the time to failure and the risk for one or more existing and future failure modes" (AFNOR, 2005).

The definition for generating a prognosis in MIL-STD 1309D is given by clause 3.1.477:

> *3.1.477 Prognosis. The use of test data in the evaluation of a system or equipment for determining the potential of impending faults*.

This definition does not refer to a quantitative time estimate for the impending faults, only to the possibility of them occurring. Prognostic goals include the notion of Remaining Useful Life (RUL):

> *Prognostics, or Predictive Diagnostics – The process of predicting the occurrence of failures to a system, device or process based on predictable time domain failures* (AFNOR, 2005)

> *Remaining Useful Life – The predicted time to a failure beyond which the system can no longer be used to meet desired performance.*

A definition of prognostics that allows for a more open and general description of both the process of generating a prognosis as well as the resulting prognostic information is given by Henry C. Pusey (Pusey, 1996) as "the art or act of predicting future conditions on the basis of present signs and symptoms".

Advanced prognostics, in much the same way as advanced diagnostics, will rely on multiple tests and methods and may be applied to conditions that cannot be fully identified and diagnosed by conventional methods. The multiplicity of tests and evidence raise it from a task to an engineering discipline or art. A definition that more accurately describes the current and future field of prognostics is:

DEFINITION 2

> ***Prognostics – The art of identifying and correlating the results of multiple tests to determine system condition and status and to generate a prediction of future status****.*

In subsequent chapters to this report, Definition 1 and Definition 2 are the basis for the discussion of diagnostics and prognostics.

Within the spectrum of diagnostics and prognostics we also include self-test or built-in-test. These can be diagnostic in nature, prognostic, or both:

> *3.1.543 Self-test. A test or series of tests, performed by a device upon itself, which shows whether or not it is operating within designed limits. This includes test programs on computers and diagnostic tests* (MIL-STD-1309D, 1992)

> *Built-in test (BIT). An integral capability of the mission system or equipment which provides an automated test capability to detect, diagnose or isolate failures*. (MIL-STD-2165, 1985)

Self-test is usually carried out by means of a digital processor and its scope is sometimes restricted to the digital portions of the equipment. This restriction does not apply to BIT.

The ability to effectively utilize advanced diagnostics and prognostics depends on a multitude of technological advances which may be specific to each diagnostic or prognostic methodology. However, the requirement for Online Monitoring (OLM) is shared by many if not a majority of advanced diagnostics and prognostics as they rely on intensive trending of temporal data.

The term On-line Monitoring in the context of nuclear plants has been used for two separate functions which are both covered in the definition that was given in the Light Water Reactor Sustainability Workshop on On-Line Monitoring Technologies (Baldwin, et al., 2010):

> *On-line monitoring: Automated methods of 1) monitoring instrumentation and assessing instrument calibration and, 2) assessing the health condition of components, equipment, and systems, including both active and passive parts of the plant, while the facility is operating.*

This report is concerned only with on-line monitoring that is required to enable AD&P (the second definition). OLM for the purpose of calibration was covered in an earlier report (Hines, et al., 2008), (NUREG/CR-6895). The performance and safety requirements of OLM techniques, as they are applied to AD&P, are essentially similar to the requirements for the purpose of online calibration. Since these have been treated comprehensively in NUREG/CR-6895 they are not discussed in this document. These requirements include technological as well as management issues: band width, resolution, as well as redundancy policies.

1.3 Scope

This report investigates AD&P as they are currently, or may be in the future, applied to equipment found at nuclear facilities. This includes both nuclear generating stations and commercial fuel cycle facilities involved in conversion, enrichment, and fuel fabrication. This effort addresses all types of equipment that support production and processing in nuclear facilities.

Although the list of applications included in this report cannot be exhaustive of the field, an attempt was made to include a sample that covers broadly the prominent techniques, particularly those believed to become relevant in licensing requests in the decades to come (e.g. items used in control systems, various sensors, transformers, structures and electromechanical motors, valves and pumps).

Safety concerns influence the scope and manner of utilization of AD&P in nuclear facilities. This report also discusses the issues of monitoring the monitor and defense in depth in this context.

Part 1: Overview of Advanced Diagnostics and Prognostics

Part 1 of this report starts with Chapter 2 "The Environment for Advanced Diagnostics and Prognostics". Chapter 2 discusses the cause and time progression of failures, the economic backdrop for AD&P, and the interaction of diagnostics and prognostics with the instrumentation and control of nuclear power plants and nuclear fuel cycle facilities independent of the type of diagnostics or prognostics that are used. Chapter 3 "Diagnostic and Prognostic Methodologies and Techniques" provides a sampling of existing and proposed techniques that cover a broad spectrum of applications. In Chapter 4 "Example Applications" five of these techniques are described in detail so that the steps necessary for their development and use become visible. Chapter 5 "Introducing Diagnostics and Prognostics to the Nuclear Power Environment" discusses ways by which AD&P may currently or in the future find its way into NPPs and NFCFs. Chapter 6, "The Future of AD&P" attempts to outline the way in which the field may develop. Appendix A provides more detail on the example techniques as well as taxonomies that permit generalizing some of their essential features. Appendix B lists organizations, publications and conferences in the growing field of diagnostics and prognostics.

2 The Environment for Advanced Diagnostics and Prognostics

This chapter addresses factors that affect selection and deployment of advanced diagnostics and prognostics in nuclear power plants and fuel cycle facilities regardless of the techniques employed. Diagnostics requires an assessment of the current state of the plant equipment, and prognostics involves using a history of equipment states to generate an estimate of a future equipment state. Understanding the failure process and its manifestations is essential for all activities in this field and that topic is addressed in section 2.1 and its subsections. All diagnostic and prognostic techniques depend on information about how the plant and equipment state is acquired. This topic is addressed in Section 2.2 and points to the crucial role of instrumentation. Nuclear facilities of the next generation will make increased use of electronic instrumentation and Section 2.3 discusses techniques for prevention and detection of failures in electronic instruments. Section 2.4 discusses the economic motivation that may lead the industry to adoption of advanced diagnostics and prognostics. A summary paragraph concludes this chapter.

2.1 An Introduction to the Cause of Failures

The discussion of cause of failures begins with an idealized case where there is only one failure mode that affects plant operations and where the distributions of load and strength are known. Dynamic elements of the load (cycling vibrations, etc.) are initially neglected. The approach can be applied directly to mechanical structures but is also a conceptual basis for failures in other areas.

2.1.1 The Mathematical Model

In general, failure occurs when the load (with respect to the failure mode) exceeds the strength. This can be caused by an increase in the load (induced failure) or by a decrease in strength (due to fatigue or time related wear-out).

Hypothetical load and strength distributions are shown in Figure 2.1. Arbitrary units of load or strength are plotted along the horizontal axis, and the vertical axis represents the probability density of the load or strength taking the values along the x-axis. The probability for failure at any point is the product of two factors

- The probability that the strength has the value noted at the x-axis and
- The cumulative probability that the load has at least that value

Typically, because the centers of the strength and load distributions are separated and the tails of the distributions are small one can visualize this product by means of the "overlap area". In this instance there is indeed an area of load and strength overlap at about 1900 x-axis units as shown in the enlarged view of Figure 2-2: The section from around 1700 x-axis units to approximately 2100 x-axis units will generate the main contribution to the overall failure probability. In the left part of the figure (near 1700 x-axis units) the failure probability is low because only a very small part of the strength distribution lies there: the system is unlikely to be at a state of such low strength.   Likewise, towards the right side of the figure (near 2100 units), the failure probability is small because only a very small portion of the load distribution reaches this value: it is unlikely that the system will be loaded to this extent. These curves represent a specific state of the system. They reflect the load profile (which will vary between installations and usage patterns) and they reflect the system history (simply put the age, experience and wear-out reflected in the strength distribution). This diagram can represent a young system that will fail only under extreme (continuous or random/transient) loads or an older system that due to wear will show a significant low strength tail in the distribution. For any equipment there will be a shift of the strength curve downwards and there may be transient shifts of the load upward. Hence with time, the product of these distributions will increase with potentially transient large fluctuations due to load variations. Aside from these generalities, it is difficult to extract from this representation failure probabilities that can be the source for a reliable diagnostic or prognostic warning.

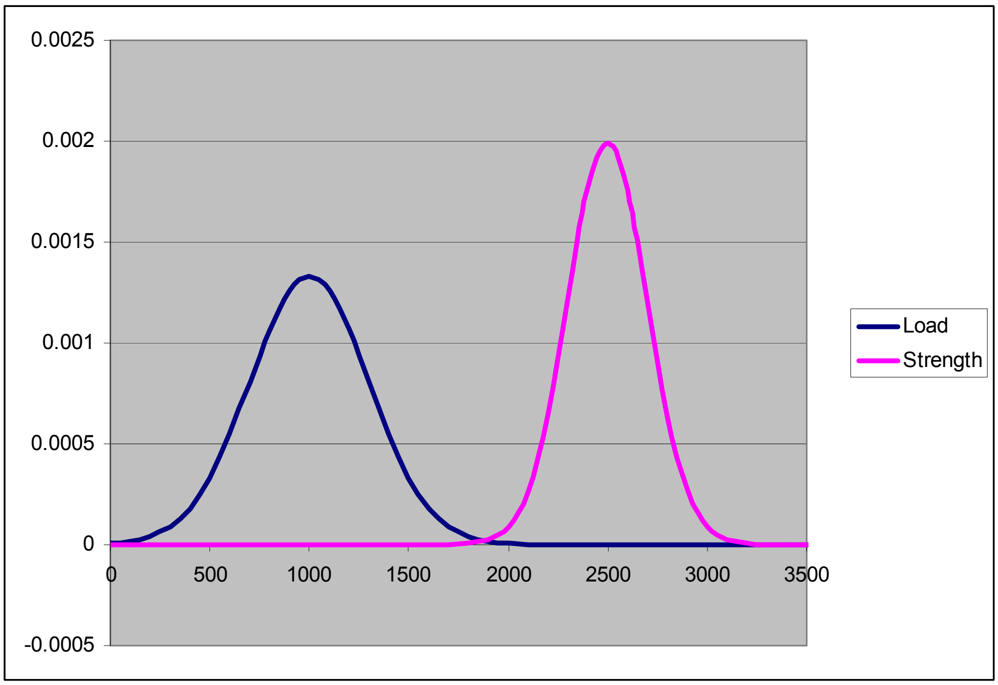

FIGURE 2-1 PROBABILITY DENSITY OF LOAD AND STRENGTH

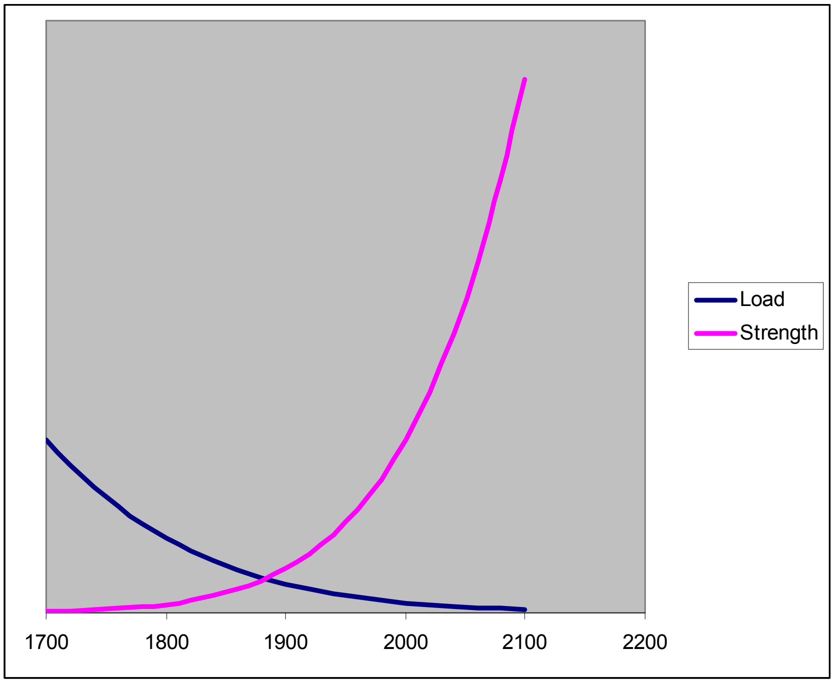

FIGURE 2-2 OVERLAP OF LOAD AND STRENGTH FUNCTIONS

2.1.2 Failure – Beyond Mathematical Models

If the types of distributions and their parameters are known, a failure probability can be calculated by established methods. The precision with which the result can be displayed may be mistaken for accuracy of a safety prediction. This invitingly easy procedure masks several difficulties that affect all approaches to AD&P. These include the physical (real world) definition of failure, the uncertainties in the load and strength parameter estimation, as well as multiplicity of failure modes and their possible interactions. In order to implement a diagnostic procedure one must know how to infer the load and strength distributions from the available measurements. In order to implement this knowledge in a prognostic procedure, one must also know how the curves evolve with time and usage.

In diagnostics the central problem is the identification of a failed or degraded element and in prognostics it is to estimate the time to failure on an element. Both depend on a definition of failure. Does an item fail when it can no longer perform a specified function, perhaps even destroys itself, or does it fail as soon as it deviates in any way from its specification? It is useful to shift the terminology and focus from failure to the end of useful life: the point at which the system requires maintenance attention or replacement (either in anticipation of failure or after failure). The end of useful life threshold of an item may depend on the application, its importance to safety, the required availability and other factors. The best recognized end of life used to be burn-out of an incandescent light bulb. But in many commercial settings bulbs are replaced when the light output drops below a given fraction of the original value, thus making even this end of life event subject to empirical criteria, In addition, the selection of an end of useful life criterion will have administrative and resource implications (state of plant required for maintenance, personnel and spares availability). Thresholds that are set for very early recognition of failure result in unnecessary maintenance or replacement; if failure is recognized very late the reliability of the system will suffer as the approach to EOL may be missed. The economic implications of this are presented in subsection 2.4.

In most cases an appropriate definition of end of useful life can be arrived at by restricting it to a specific failure mode and accepting a threshold that is obtained from empirical data. Thus, even where there is a validated mathematical model for a failure process there will be a subjective element in setting the criterion for end of useful life. This issue is discussed in more detail in section 2.1.4.

The task of generating a credible model for a given failure mode involves selecting suitable statistical distributions either for load and strength or, more frequently, for time to failure as a random variable and then estimating parameters from the available data. There is no lack of statistical tools to help with this task: goodness of fit tests (Taylor, 1997) can validate the model selection, and regression techniques (Fan & Gijbels, 1996) can be used to estimate parameters. However, most statistical techniques will evaluate the distribution over its entire range. Naturally they are weighted towards the center of the distribution which is the high probability region. However, to estimate the end of life, one is actually interested in accuracy of the tails of the distributions as this is where the significant contributions to the failure probability reside. In the region of high probability of the strength distribution the load distribution will be small, therefore offering only an uncertain contribution to the overall failure probability. Conversely, in the area of high probability of the load distribution, the strength probability will be very small, leading to the same uncertainty, The conventional goodness of fit tests and parameter estimators can provide no assurance of validity at the extremes, the area where the probability of failure for components of nuclear plants is typically evaluated, e. g., at 10^{-3} or less. There are also non-parametric methods (Tukey, 1977) available but they either require large amounts of data in the range of interest, or else result in very wide confidence intervals. Hence they are less useful than parametric methods in generating reliable diagnostic and prognostic results.

In spite of their limited accuracy, statistical failure models are useful in the evaluation of alternatives and in outlining rather than pinpointing failure probabilities. Defense in depth which is mentioned in several places in this report is one way of accommodating the limitations of these models.

2.1.3 Time Progression of Failure Probability

Over time the failure probability introduced in section 2.1.1 may change. Statisticians may view this as primarily due to a decrease in the mean strength and an increase in the standard deviation of strength. Materials scientists may view it as a result of fatigue, stress corrosion or similar processes. In either view, the failure probability will exhibit an increasing trend as shown in Figure 2-3.

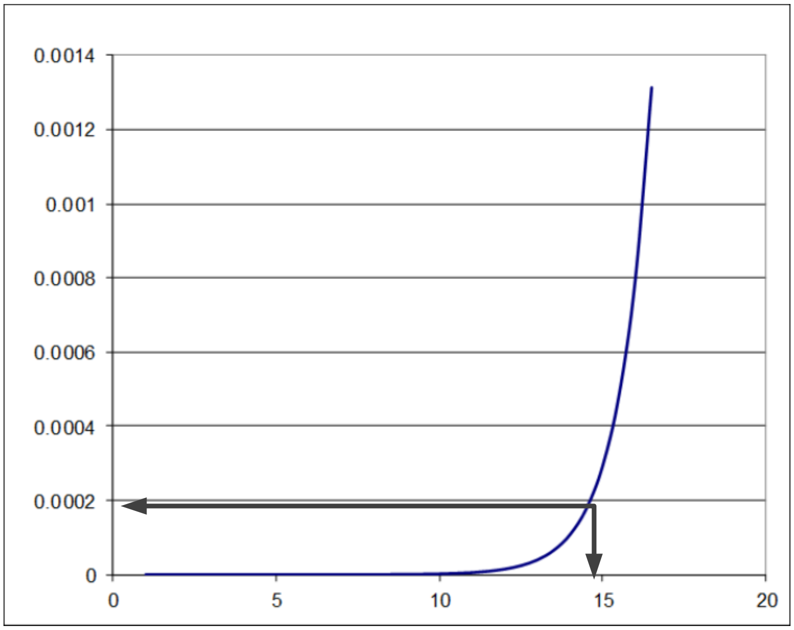

FIGURE 2-3 INCREASE IN FAILURE PROBABILITY OVER TIME

The horizontal axis represents arbitrary units of duty time of an element; the vertical axis represents failure probability. The figure is hypothetical and the scale markings are provided to facilitate reference to segments of the curve. Eventually the failure probability will level out and not increase beyond 1. In this representation the end of useful life may be indicated by the maximum acceptable failure probability. As an example, if 0.0002 is selected, the useful life is slightly under 15 units of time. If the equipment has operated for 10 units of time the remaining useful life would be estimated as 5 units of time.

A refinement of this methodology recognizes that the progression to failure is not simply a matter of time but also depends on the stress experienced during the interval. A very common use of this approach is when a used car is evaluated on both age and miles driven. In NPPs an overall indicator of the stress experienced by the components is the output power level. The relationship between output power and stress on components may not be linear and may vary among components. The remaining life of the turbine and generator are much more likely to be affected by the output power level of the reactor than the control room ventilation system. Other factors that may affect the remaining useful life are temperature cycling and load transients. These considerations of the time progression of the failure probability are applicable to all AD&P approaches.

2.1.4 End of Life (EOL)

The previous discussion has been concerned with the processes leading to failure or EOL. The current heading looks at management issues and how the EOL definition impacts the validity of diagnostic or prognostic analyses. In this context the term EOL includes three possible events

- Physical failure;
- Reaching a condition where economic factors indicate replacement or repair (see below);
- Reaching a condition where possible damage to associated equipment makes replacement or repair desirable.

For each system, EOL should be defined while considering: criticality of equipment, the time-progression to failure, the specific maintenance procedures and resources. EOL is defined as a measurable state or condition of the equipment. Once it is established, it pertains both to load induced failures and time-related wear out, which identify the two ends of the spectrum of failure dynamics. Whether the strength distribution moves to lower values, or increases in variance; or the load distribution increases, the overlap of non-negligible areas of the distributions will lead to measurable conditions that have the same effect on EOL.

An economic criterion for end of life is shown in Figure 2-4 and may be constructed as shown on the following page.

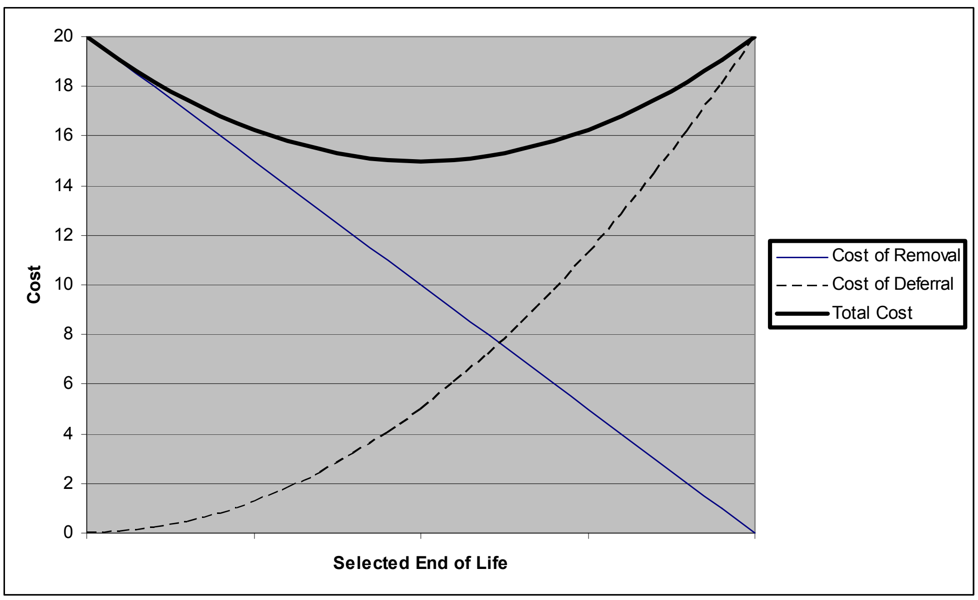

FIGURE 2-4 ECONOMIC END OF LIFE

- Deferring the repair or replacement of an element will in general increase the cost of maintenance (included in this may be the cost of plant shut-down due to complete failure of the element). This is shown as the Cost of Deferral in Figure 2-4 and it is related to the increase in failure probability shown in Figure 2-3.

- Conducting repair or replacement early will deprive the operator of remaining useful life of the element. This is shown as Cost of Removal from Service in Figure 2-4 and is assumed to be a linear function of time up to the point where complete failure of the element is a certainty (at the right in the figure).

The minimum of the total cost curve may be termed the economically optimum end of life. The minimum of the total cost curve is shallow (this is a general and important characteristic of these trade-off representations), meaning that the cost will not significantly increase by moving the selected end of life a small distance to the left or right. This is fortunate because of the difficulty of determining the parameters for this economic EOL model. Although it is unlikely that economic criteria will be rigorously applied in this regard, the concepts developed here will enter into making EOL selection or assumptions, particularly in non-safety critical plant functions.

In the NPP environment there are other significant factors entering into the decisions regarding the time to repair or replace equipment, including opportunistic access during plant shut-down to locations that are inaccessible during normal plant operation.

Some other factors entering into EOL selection may include

- A given percentage reduction in the original strength or output of an element; the percentage may be in accordance with an accepted standard
- Deviation from the equipment specification
- Output degradation that causes performance degradation of the next higher level in the equipment hierarchy.

As these considerations indicate there are no universally accepted rules for EOL definition. However, EOL assumptions in connection with diagnostics and prognostics should meet the following criteria:

1. Is the EOL definition clearly stated and is its basis described?
2. Is there experience with the use of this EOL definition?
3. Does the definition require additional instrumentation or computing? What is the experience with these additional capabilities?
4. Will equipment operating at the EOL threshold still permit the next higher levels in the hierarchy to meet their performance specification under all design basis conditions, including failure of a redundant element?

2.2 Assessing the Plant and Equipment State

One of the key questions for plant operators is: "Is the plant in an operational state?" This question is asked with respect to each attribute required for safe and effective operation. If the answer is yes for the current attribute, the question is repeated for the next attribute of plant operation. If the answer is no, the next question is "What action needs to be taken to bring the plant to an operational state?" This highly simplified diagnostic loop is diagrammed in Figure 2-5. The term *plant* in this and the following figures should be understood as *plant and/or equipment*. The attributes to be observed are items taken from the plant or equipment specification, shown in the figures as "Plant Specification Item". The process is visualized as sequential but in practice some observations may be taken at the same timhhe.

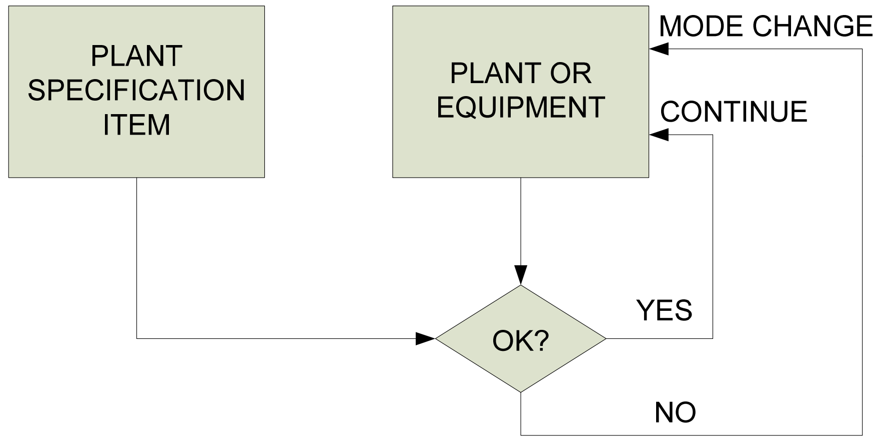

FIGURE 2-5 SIMPLIFIED DIAGNOSTIC LOOP

To be in an operational state the plant or equipment must meet every item of its specification. The terms “operational” and ”non-operational” have regulatory implications that are not addressed here; the interaction of AD&P and the plant Technical Specification is discussed in Section 7.3. The action to be taken when there is a deviation from the specification is termed ‘mode change’ in the figure, and this can mean maintenance action, reduction in output, complete shutdown, or switching from the primary to a stand-by channel.

This report is concerned with AD&P as it is applied to all types of equipment in NPP and NFCF. However, because AD&P usually depend on automated, and often high frequency data collection, one will often find they are supported by plant instrumentation. When discussing AD&P even of purely mechanical structures this must be taken into account, and one should also analyze the failure behavior of the supporting instrumentation. Knowledge of the plant state is obtained through instrumentation as shown in Figure 2-6. This introduces ambiguity into the assessment: is a deviation from normal indication the result of a plant state or of an instrumentation problem? Even worse, can an abnormal plant state be masked by an instrumentation failure? The detection of instrumentation failures will be further explored in section 2.3.

To assess the operational or safety consequences of potential failure modes it is convenient to consider two types of failure modes of the instrumentation separately:

1. Masking failure modes in which the failed instrumentation mimics a well performing plant, regardless of the actual state
2. All other instrumentation failure modes (non-masking).

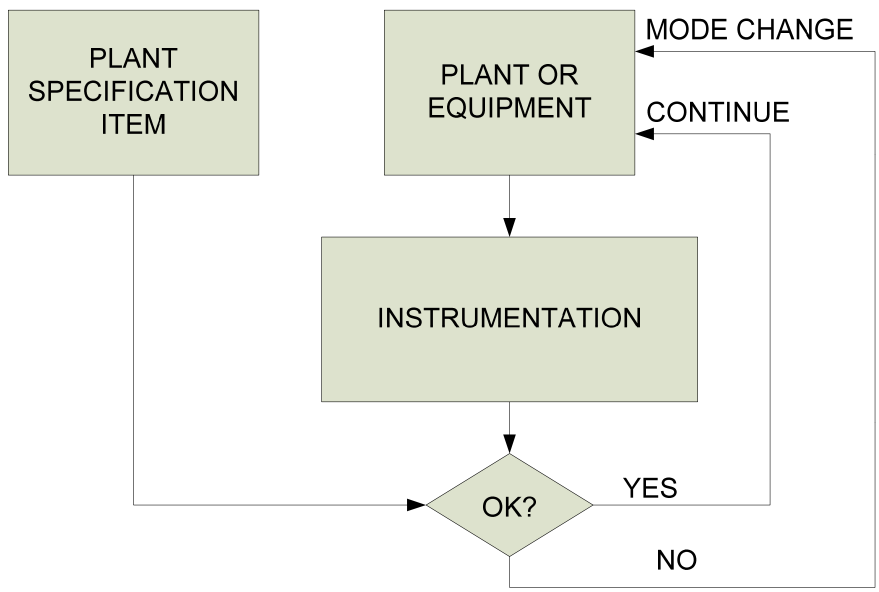

FIGURE 2-6 THE CRUCIAL ROLE OF INSTRUMENTATION

The combinations of plant or equipment and instrumentation states and the immediate actions based on the indications are summarized in Table 2-1.

Table 2-1 Immediate Action on Indications

		Instrumentation State		
		Operational	Failed Masking	Failed Non-Masking
Plant or Equipment State	Operational	None required	Non-immediate maintenance required	Intervention required
	Failed	Required and taken	Required but not taken	Required and taken

As long as the plant and the instrumentation are operational, there is no action required. When the plant is operational and the instrumentation fails in a masking mode there is still no immediate safety related action required but the instrumentation has to be repaired. When the plant is operational and the instrumentation fails without masking, the immediate action the result will be an unnecessary repair of plant equipment. Therefore, instrumentation should be provided with diagnostics that resolve the ambiguity. When the plant fails and the instrumentation is operational, maintenance is properly directed at the plant. Instrumentation diagnostics can confirm that this is the appropriate action.

However, if the plant fails and the instrumentation fails in a masking mode, a potentially much more dangerous condition arises. This represents a latent plant or equipment failure where mitigation provisions are bypassed because the failure is not observed. The prevention of this condition for critical functions must be a primary focus of any diagnostic effort. A latent failure in a normally unused function, e. g., one that is used only for mitigation or recovery, represents a particularly dangerous state because it can disable the entire mitigation or recovery process. The prevention of such failures is discussed in the next section.

The last combination in Table 2-1 represents a plant failure and a non-masking instrumentation failure. The immediate efforts are the same as for any detected plant failure and intervention is required. Instrumentation diagnostics should be provided to present a true picture of this condition.

2.3 Prevention and Detection of Instrumentation Failures

As already mentioned, the implementation of AD&P programs involves use of instrumentation. The preceding section has shown the importance of monitoring instrument operation so that failure of the instrumentation can be distinguished from a plant failure, and particularly to prevent masking instrumentation failures. Even though the probability of an instrumentation failure in the masking mode may be very low (and may be further reduced by AD&P efforts) it must be protected against, because it can mask unsafe conditions.

The following discussion looks at measures to prevent the effects of instrumentation failures, particularly those that lead to potentially catastrophic latent plant or equipment failures. The material is particularly aimed at electronic instrumentation where random failures predominate. The topics are:

- Self-monitoring (“smart”) instrumentation
- Physical redundancy
- Analytical redundancy

These measures that are individually described below are not mutually exclusive and can be combined in any manner. This furnishes an opportunity for defense-in-depth.

2.3.1 Self-monitoring (“Smart”) Instrumentation

Smart instrumentation includes a monitoring function that ideally signals any deviation from the specified performance and that may be considered as a diagnostic provision. For the system designer a major advantage is that this is a self-contained solution to the instrumentation failure problem. When the monitor detects a deviation from the specified performance, the instrument output is inhibited; thus masking failures are made much less likely. The operation of smart instrumentation can be diagrammed as shown in Figure 2-7.

While this may be viewed as just moving the ambiguity problem to the next lower level, there are several factors that can reduce the probability of an undetected masking failure by at least an order of magnitude. The monitor is usually much less complex than the instrumentation and it is designed to have a much lower failure probability. In addition the design will specifically aim at avoiding masking failure modes, e. g., by making the *OK* indication a pattern (e. g., three evenly spaced pulses) rather than a single line going high or low.

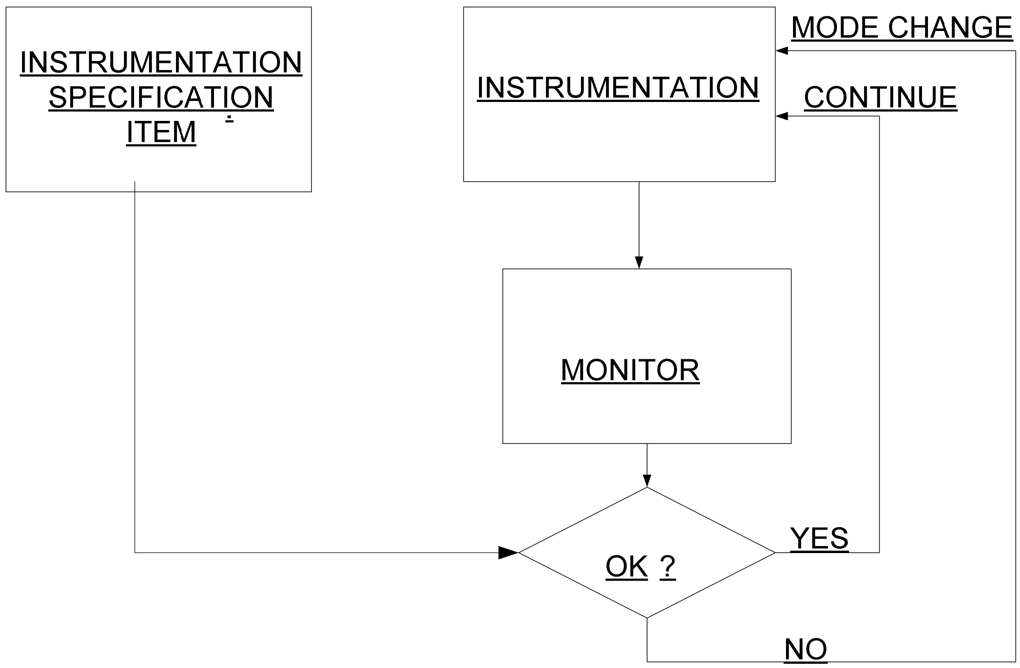

FIGURE 2-7 SMART INSTRUMENTATION

2.3.2 Physical Redundancy

Physical redundancy of instrumentation channels is frequently employed in current NPPs and NFCFs. It is here discussed as a tool for detecting masking instrumentation failures. A masking instrumentation failure is a rare event and thus it should be possible to transform this into a highly unlikely event by using two separate instrumentation functions in a logical AND configuration (both must indicate the plant to be operational to yield a YES output). Such an arrangement is shown in Figure 2-8. For the system designer this is attractive if the existing instrumentation has been shown to be dependable so that installation of an additional component does not represent undue risk of false alarms or maintenance requirements.

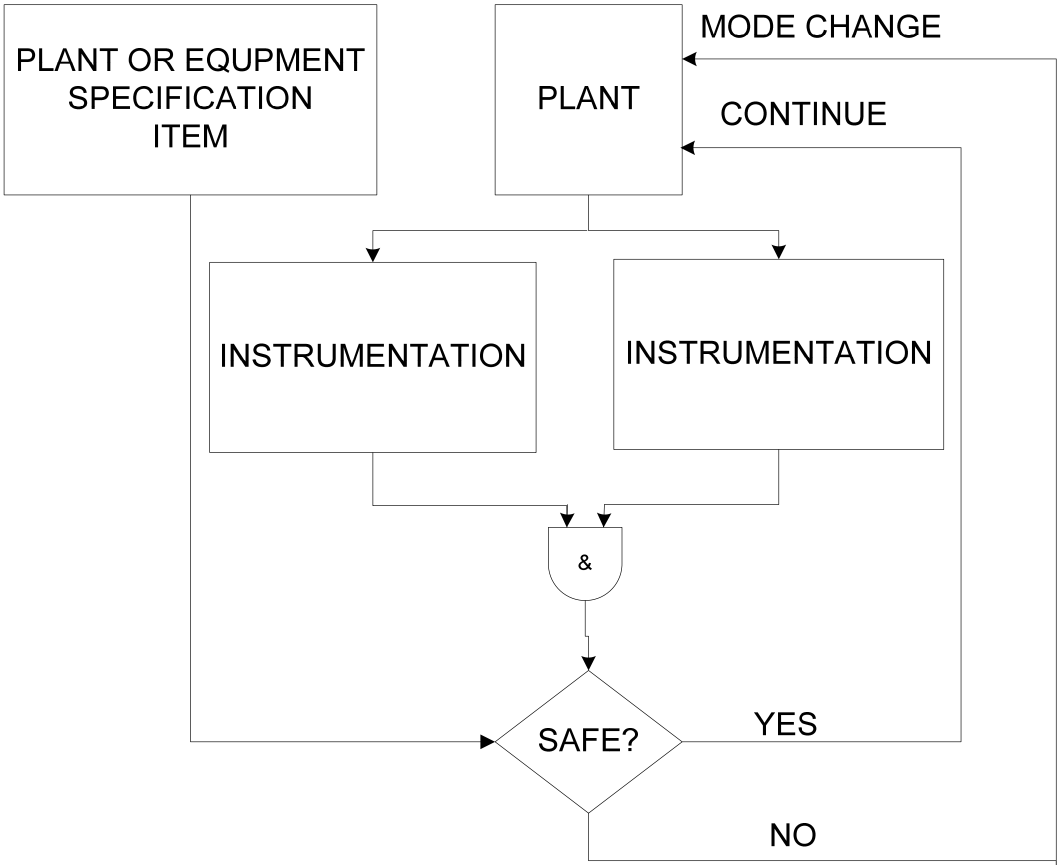

FIGURE 2-8 PHYSICAL REDUNDANCY

If the AND gate receives unequal inputs it indicates an instrumentation failure. If it receives two NO inputs it indicates a plant failure. The Instrumentation blocks in Figure 2-7 include not only the measurement and analysis component but also the communication paths up until the point that they enter the "&" gate. If instrumentation is more than doubly redundant, the above scheme can be applied to each combination of two of the channels. In case of an instrumentation failure this will permit identification of the failed channel.

For masking failures in particular, an additional monitoring step can be useful: sampling the difference of the output of two or more independent instrumentation channels. In the case of a masking failure the AND gate may accept the two signals and miss small variations in the output. However, monitoring the difference between the two signals will highlight even small variations. If these small variations either exceed a certain threshold (can be much smaller than the threshold of the AND gate) over a certain period of time, or show certain patterns it can be an indication of instrumentation wear-out or degradation.

2.3.3 Analytical Redundancy

In analytical redundancy the equivalent of an essential instrumentation item is constructed from one or several other item(s) based on an analytical relationship between them. The output of the analytical redundant configuration can be used as a redundant element to prevent fault masking failures similar to the configuration shown in Figure 2- 8. A simple analytical equivalent is shown in Figure 2-9 in which the critical data item is the pressure at the output of User A (PA). An analytically redundant data item can be constructed from the pressure at the output of User B (PB) plus the differential pressure (DP), treating the latter as an arithmetic signed quantity. From the system designer's point of view this appears as a very advantageous solution since all the major pieces are already in place and the only new requirement is a combining algorithm.

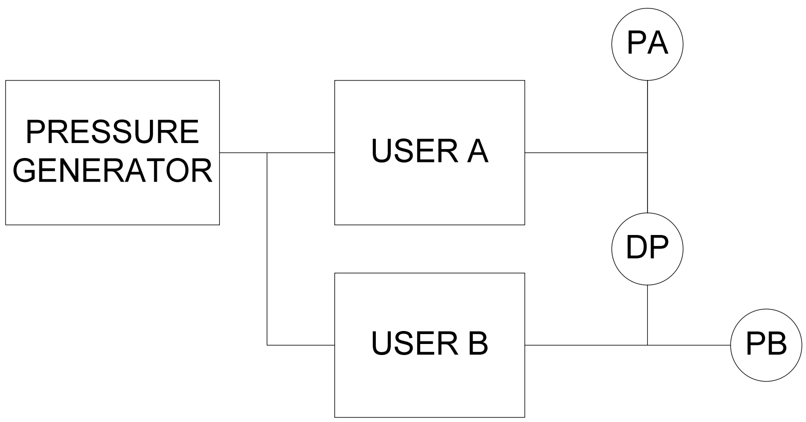

FIGURE 2-9 ANALYTICAL EQUIVALENT OF PA

2.3.4 Typical Assessment Questions for Failure Mitigation

Applications of advanced diagnostics and prognostics will often require the use of instrumentation for rapid assessment of equipment states. Confidence in this instrumentation is a necessary prerequisite for the implementation of the AD&P. As discussed in the introduction to this document, this report does not address online monitoring for the extension of safety critical sensor calibration intervals. These are covered by NUREG/CR-6895 (Hines, et al., 2008). Therefore OLM is not discussed in detail. That said, online monitoring is usually a requirement for an AD&P program, and therefore it is always in the background of such applications. Concern with the instrumentation suitability and dependability for AD&P can give rise to questions such as the following (these are by no means intended to exclude others):

Questions when smart instruments are being considered include:

1. Complexity – does the inclusion of the monitor raise the complexity of the instrumentation to an unacceptable level?
2. How dependable is the operation of the monitor? Can the operation of the monitor be observed and tested by a supervisory program?
3. Will the expected frequency of shut-down of a given instrument present a plant safety problem? In particular will the rate of false positive alarms (events where a positive diagnosis of failure is false and the equipment has not failed, or is not close to failure) affect plant safety?

Questions when physical redundancy or sampling is being considered include:

4. Correlated or common mode failures – are there design features that can cause both components to fail in the masking mode under some external stimulus (earthquake, fire, etc.)? This can be alleviated by using diverse designs but that negates the benefit of using one trusted component.
5. Can failures in the combining algorithm or its implementation permit a single masking output to be interpreted as a double masking output?
6. Can an undetected failure in one of the instrumentation channels permit a failure in the second channel to propagate unchecked? This concern can be substantially alleviated by periodic testing of the individual channels through a supervisory program.
7. Can failures in the sampling or modulation circuits permit a single masking output to be interpreted as a double masking output?

Questions when analytical redundancy is being considered include but are not limited to:

8. Will the combining algorithm hold under all conditions? Consider specifically the transient response of all elements involved.
9. Will a failure of the combining algorithm permit either the primary or the analytical channel alone to furnish output?
10. Will a single channel failure go undetected? This concern can be substantially alleviated by periodic testing of the individual channels through a supervisory program.

2.4 Economics of Diagnostics and Prognostics in the Plant Environment

The benefits of diagnostics and prognostics are generally more widely publicized than their cost (Feldman, et al., 2008), with the latter particularly difficult to estimate where compliance with industry standards or regulatory approval is required. For this reason it is expected that AD&P in nuclear power plants and fuel cycle facilities will initially be introduced in plant systems that are not safety related.

In manufacturing, transportation and process industries diagnostics are an accepted part of plant and vehicle operations because they offer the following economic benefits, among others:

- Permit component failures to be isolated at a local level before they can propagate to global effects (e. g., replacement of a turbine blade rather than the turbine).

- Provide information to maintenance personnel that permits them to arrive with the right tools and replacement parts; an important associated benefit is the early resumption of operations.
- Facilitate the collection of fleet-wide data that can lead to detection of failure trends affecting a universe of components (more about this later).

Prognostics offer the following additional benefits, again not restricted to the nuclear industry and without claiming to be a comprehensive listing:

- Reducing the need for very expensive find-and-fix maintenance.
- Permitting the conversion of necessarily conservative fixed schedule maintenance into condition based maintenance.
- Avoiding the need for a large spare parts inventory by facilitating just-in-time ordering.

The term *prognostics* usually means a process for estimating remaining useful life or determining an economically optimal replacement time. Most current literature assumes that the decision making is at least partly automated but this is not necessary to reap substantial benefits. Experts are performing what may be termed manual prognostics when they decide that a feedwater pump needs to be replaced during the current refueling outage to avoid the very large cost of an unscheduled plant shutdown. The manual data taking and trending involved in this work are usually highly labor-intensive and therefore significant economic benefits can be anticipated from automating it. These benefits can be achieved without most of the R&D investment that is required for establishing a basis for conventional prognostics (special sensors, computers, etc.). The change to an automated system will usually require a change in the TS and NRC agreement if it involves altering a regulated inspection schedule.

At this point some fundamentals of NPP economics may be informative. Operations and maintenance costs account for 60 – 70% of the total cost of generating nuclear power in the United States (Coble, et al., 2012), and 80% of the O&M cost is accounted for by labor (Wacker, et al., 2007). Thus each plant operator can be expected to be motivated to automate maintenance and thus to reduce the labor expense. On a wider scale it has been estimated that savings of over $1 billion per year are possible in the United States when prognostics and health management are applied to all key equipment in legacy power plants (Bond, et al., 2011).

In 2008 Exelon, one of the largest operators of NPPs in the United States, installed InStep's PRiSM software for Centralized Performance Monitoring (a form of fleet-wide data collection and analysis) (Newswire, 2008). With 500 deployed plant equipment computer models, it is estimated that Exelon avoided over $500,000 in equipment and production losses in the first two months of operation from early warning notification of potential equipment problems.

So far the economic factors all seem to favor adoption of advanced diagnostics and prognostics. But of course their application to NPPs and NFCFs cannot be at the expense of safety. Therefore all assessment issues, sometimes presented as questions, in the previous headings remain valid. In addition, whenever one considers the automation of an activity that had been carried out by a human being, it must be asked whether collateral surveillance is not being jeopardized. Do the maintainers only read a dial and enter a value in a data sheet, or do they also look for leaks on the floor or an unusual smell? The continued need for unstructured surveillance must be considered in the economic analysis when automation replaces human activities.

2.5 Summary

This chapter has introduced models that explain the failure process and several definitions of failure or end of life. Diagnostics and prognostics are concerned with observing and assessing the current state of the plant (diagnostics) and interpreting the time history of observations in terms of time to required maintenance or remaining useful life (prognostics). The observations are mostly carried out by means of instrumentation, and this implies that an indication of an abnormal plant state can be due to either a failure of the plant or of the instrumentation. Moreover, unusual instrumentation failures may mask plant failures and may thus impede the timely implementation of corrective measures. These ambiguities can be resolved by use of "smart" (self-checking) sensors or by employment of redundant sensors but these techniques have limitations and introduce new vulnerabilities. Assessment questions have been proposed to identify the most effective measures

Advanced diagnostics and prognostics promise savings in maintenance expense and reductions in plant down time. These economic incentives can be expected to be important factors leading to the adoption of AD&P in the new generation of nuclear power plants and fuel cycle facilities and in the life extension of existing ones. Tentative steps in that direction are being taken by the adoption of digital instrumentation and remote monitoring networks in the non-safety related aspects of plant operation. The success and operating experience of these will lead to guidelines for adoption in safety related applications.

3 Diagnostic and Prognostic Techniques and Methodologies

This chapter surveys AD&P techniques and methodologies compiled from a review of hundreds of published documents and information obtained from interviews with academic and industry experts. Methods are grouped into categories that use similar instrumentation or models. This survey is a representative (rather than comprehensive) list of state-of-the-art techniques used in AD&P. Other techniques and methodologies may exist or be in development or may be outside the group headings chosen for this report.

All technologies listed in this chapter are discussed in more detail in Appendix A. Appendix A also provides two alternate groupings that provide insight into the equipment in which these techniques have been or could be implemented.

3.1 Canaries

The canary subgroup includes techniques that provide warning that conditions are approaching limits at which an item will fail. These are mostly used in electronic circuits and are implemented by a sacrificial "cell" with lower threshold vulnerabilities than the protected item. The limitation of a canary cell as a technique for AD&P is that it offers little lead time for corrective action. Its strength is that it is simple and will protect a costly system from failure. Examples include:

- Fuses: These are traditionally used as warning that current through an electronic circuit is approaching an upper limit. As a diagnostic tool a fuse is rather non-specific in that it only diagnoses an unhealthy condition but usually will not indicate the cause of the condition. It is not a prognostic predictor as it can only indicate that failure has occurred. (D-1 in Appendix A)
- CMOS canary cells: these cells are designed to be slightly more sensitive to the same stressors (voltage, current, temperature, humidity, radiation and vibration) as the operational cells, therefore failing earlier as conditions approach the operational limits. (D-2 in Appendix A)
- Solder joint canary cells: these are often implemented at the perimeter of a multi pin contact (edge connectors). The edge experiences failure inducing conditions such as vibration, humidity and contamination more intensely and therefore will provide an indication of worsening of conditions and approaching failure. As a canary cell, this type of implementation offers a prognostic window of time to repair the component. It is usually implemented in such a way that a short will not affect the functionality of the rest of the contact. (D-3 in Appendix A)
- Corrosion canary cells: used in electronics and designed to experience corrosion stressors and preempt part failure due to corrosion effects. (D-4 in Appendix A)

3.2 Performance Monitoring Techniques

This group of techniques is characterized by a focus on the actual performance of the equipment. These techniques monitor various performance metrics measured either internally or externally. Trends in the performance offer insight into the condition of the item which can be used both for diagnostics and prognostics. One advantage of these techniques lies in the fact that one is usually not required to add new measurement equipment to a component: the indicator is often an input to other equipment, and therefore easy to monitor without design change. Another advantage is that monitoring the performance can often provide a large prognostic window, which could allow for better maintenance planning and operations. In some instances parameter thresholds are used to identify degradation and in some cases signature patterns (e.g. amplitude trend dynamics or fluctuation patterns) are used to identify degradation. In particular "marginal checking" of very small changes to performance metrics provide information on degradation. Examples of performance monitoring techniques include:

- Built In Current Sensors (BICS): these are applied to CMOS primitives and single die ICs where they monitor supply current. Increase in current above a threshold is used to identify fault conditions. (D-5 in Appendix A)
- MOSFET performance signature: multiple performance signatures are trended and compared with prior measurements. (D-6 in Appendix A)
- Marginal checking of cables and connectors: Impedance changes are monitored. (D-7 in Appendix A)
- Marginal checking of voltage controlled oscillators: monitoring of several types of performance parameters such as output frequency, power losses and efficiency, phase distortion and noise. (D-8 in Appendix A)
- Marginal checking of Field Effect Transistors: monitoring of leakage currents (drain-source and gate) and drain-source resistance. (D-9 in Appendix A)
- Marginal checking of ceramic chip capacitors: monitoring of leakage current, resistance, dissipation factors as well as RF noise. (D-10 in Appendix A)
- Marginal checking of diodes: monitoring of reverse leakage current, forward voltage drop, thermal resistance, power dissipation and RF noise. (D-11 in Appendix A)
- Marginal checking of electrolytic capacitors through measurement of leakage current and resistance, dissipation factor and RF noise. (D-12 in Appendix A)
- Marginal checking of RF power amplifiers: monitoring of performance through Voltage Standing Wave Ratio (VSWR), power dissipation and leakage current. (D-13 in Appendix A)
- Marginal checking of CMOS ICs: monitoring of supply current and leakage, operational signature, current noise and logic level variations. (D-16 in Appendix A)
- Load cycle monitoring of electronic assemblies: features of the load cycles include cyclic range, mean load, rate of load change, dwell time. (D-15 in Appendix A)
- Monitoring of pulse width modulation of Voltage Source Inverters (VSI). (D-18 in Appendix A)
- Resistance spectroscopy of Ball Grid Arrays (BGA) and other connectors with multiple solder joints: resistance monitored for pre-failure signatures. (D-19 in Appendix A)
- Monitoring of error code use in digital memories: frequency of triggering of error detecting code indicates physical aging of memory. (D-20 in Appendix A)
- Monitoring of error signal in closed loop control systems: error signals increase in magnitude, and frequency spectrum changes with physical damage processes. (D-20 in Appendix A)

- Monitoring of Pulse Width Modulation (PWM) of power devices in inverter induction motors: monitoring of output inverter currents to detect intermittent loss of firing pulses that are trended over time. (D-21 in Appendix A)
- Self-Monitoring Analysis and Reporting Technology (SMART) applied to hard drives: monitors multiple performance metrics including: head flight height, error statistics, spin down time, temperature and data transfer rates. (D-22 in Appendix A)
- Circuit as a sensor: performance monitoring of CMOS RF devices through C-V and I-V characteristics of transistor which change prior to breakdown.(H-1 in Appendix A)
- Model based performance monitoring of electro-mechanical, mechanical, electro-hydraulic Actuators: Actuator response/performance are monitored and compared with models simulating failures. (H-9 in Appendix A)
- Motor Current Signature Analysis (MCSA)/ Motor Power Signature Analysis (MPSA): the current signature as it reacts to load indicates damage. (H-10 in Appendix A)
- Monitoring of electrical signal of electromechanical generators: both frequency and phase changes are indicative of degradation. (H-11 in Appendix A)
- Measurement of quality of service of communication equipment: degradation of quality of service indicative of failure mechanisms. This can make use of standard quality of service protocols in the industry. (H-13 in Appendix A)
- Performance monitoring of pneumatic valves: monitoring of physical performance measurements: opening degree, pressure, friction coefficient, and response time. (M-6 in Appendix A)
- Measurement of response to electrical surge: these are applied to stator windings on motors to indicate short or open coils. (M-8 in Appendix A)

3.3 Self-Test

Self-test is an important diagnostic technique that can sometimes be expanded to modest prognostic capabilities. Its use is acceptable for some NPP applications because IEEE Standard 7-4.3.2 is addressed in RG 1.152. The regulatory basis and scope of regulation are discussed in Part 2 of this report.

Strictly speaking, *self-test* is only applicable to digital processors with built-in correct functionality verification tests (NRC, 2007).[2] When the test covers other components, such as auxiliary memory, communication channels, sensors and actuators it is more properly termed *built-in-test* (BIT). In this latter mode it is not restricted to digital components. Self-test may comprise check sums of read-only memories on which the operational programs are stored; execution of a number of processor steps and comparison with stored results; and operational testing of registers that are used for communicating with other components.

BIT (or BIST for built-in self-test) in addition checks for response to stimuli sent to other components, including timing checks on the responses, and can incorporate specific steps to find typical malfunctions in sensors and actuators. Assertions embedded in software that are only met if the function performs as

[2] This is consistent with the definition in BTP 7-17 "Guidance on Self-Test and Surveillance Test Provisions" (2007): A self-test is a test or series of tests performed by a device upon itself.

intended can be used to protect against many failure mechanisms. For printed circuit boards that contain a processor, BIT frequently includes boundary scan procedures (Texas Instruments, 1997) in which each input/output pin that can accept input or can be accessed for results is associated with a register. Features of this methodology were standardized by the Joint Test Action Group (JTAG) and it is sometimes just referred to as JTAG test.

Both self-test and BIT are usually performed on a channel basis. If they fail, the affected channel can be declared non-operational and this does not normally result in loss of a function because regulations require an adequate amount of redundancy. It is also usually required that physical replacement of failed items can be performed without powering down other channels.

3.3.1 Scope of Testing

Electronic components, and particularly digital ones, are subject to random failures and built-in-test is very effective in finding these. Design failures in digital hardware and software usually manifest themselves only under rare conditions and are much less likely to be detected by built-in-test, partly because assumptions that caused the faulty design may have been propagated into the design of the built-in-test. Depending on the criticality of the function served by the digital system it is desirable or essential that there be defense-in-depth provisions for detecting design flaws and if possible for recovering from them.

BIT can be performed continuously, on a device initiated condition, or on operator request. The term "continuously" should be interpreted as periodically at a sufficiently high frequency to detect the onset of a hazardous condition in sufficient time to permit managing it. The device initiated conditions usually include power-on testing. The tests are usually diagnostic in nature although trending of their performance (how long they take to process) can provide modest prognostic capability.

3.3.2 Implementation of Self-Test

BIT can be implemented on all hierarchical system levels (Moore & Damper, 1986). When applied system-wide BIT may be centralized controlling all tests and functions at all hierarchical levels; or it may be composed of several connected control centers. System-wide, centralized, BIT usually requires dedicated hardware.

The benefits of BIT are straightforward and have been recognized for over half a century:

- Faster fault localization and hence reduced down-time (Montieth, 1982)
- Fewer removals of operational units

Both lead to a significant reduction in lifecycle cost (Lappin, 1989).

- Built In Test (BIT) for hardware and software is common in logical devices as well as control systems, power supplies and other large scale systems. BITs are categorized according to their operation as: Interruptive, Continuous and Periodic. (D-14 in Appendix A)

- Self-Monitoring Analysis and Reporting Technology (SMART) is comprised of a set of self-tests applied mainly at start-up to hard disk drives. Tests focus on performance metrics and this technology is also categorized under the performance monitoring techniques of Section 3.2 above. (D-22 in Appendix A)

3.4 Multivariate Analysis

The group under this title consists of techniques that require analysis of many variables. This category focuses on methods that either require large scale pattern classification because a diagnosis requires analysis of many data features, or methods that rely on different features as evidence for a single diagnostic or prognostic. Examples include:

- Large scale pattern recognition based on multivariate features such as: Support Vector Machines (SVM), Support Vector Classification (SVC), Support Vector Regression (SVR). These are mainly applied to electronic systems but mechanical applications exist as well. (D-24 in Appendix A)
- Distance Metrics are used to reduce multivariate data to univariate data (D-25 in Appendix A)
- Projection Pursuit Analysis is another means of multivariate analysis of large systems generating very diverse measurements for AD&P. (D-26 in Appendix A)
- Continuous System Telemetry Harness (CSTH) is a multivariate diagnostic method applied to computer systems (both hardware and software) that combines many types of measurements (performance, errors, canary cells). (D-27 in Appendix A)
- Bayesian model-based diagnostics can be applied to electrical power systems using data collected from multiple types of sensors. (M-10 in Appendix A)

3.5 Life Consumption Monitoring

Life consumption monitoring techniques build on the availability of data that is directly related to the conditions leading to life consumption, rather than the condition of the actual equipment. These can be either indirect measurements of material consumption (e.g. particles) or they can be direct measurements of various known stressors (such as temperature or vibrations). The data is then applied to life consumption models that may estimate degree of degradation as well as rate of degradation. The technique is used wherever such measurements are possible both in electronic and mechanical systems. Examples include:

- Solder joints: Temperature and vibrations are known stressors and these are monitored for RUL estimate. (H-2 in Appendix A)
- Electronic/digital modules: temperature and vibration are monitored to predict RUL. (H-8 in Appendix A)
- Flow accelerated corrosion can be detected via electrochemical and vibration sensors that identify flow accelerated corrosion at pipe elbows. (M-1 in Appendix A)
- Smart oil analysis provides information on type and size of contaminants indicating corrosion and life consumption. (M-4 in Appendix A)
- Dissolved Gas Analysis is applied to insulating mineral oil in transformers to identify faults and degradation. (H-6 in Appendix A)

- Pneumatic valves: the application of a damage based model to pneumatic valves draws on life consumption data such as friction and degree of opening. (M-6 in Appendix A)

3.6 Vibration Analysis

Vibration analysis is a mature and widely used diagnostic technique. It is mainly applied to mechanical (both static and dynamic) systems as well as to electromechanical components. Examples of the application of vibration analysis include:

- Rotating elements: vibration sensors can measure displacement, velocity and/or acceleration; each offering information on different frequencies and amplitudes of vibration. (H-4 in Appendix A)
- Transformers: measurements of vibration of magnetic cores and windings are used to diagnose structural degradation. (H-5 in Appendix A)

3.7 Acoustic Techniques

Sound waves have been used for decades to diagnose the condition of both passive and active components. Although more suitable for mechanical systems, sound is also used in electromechanical systems. The application to diagnostics and prognostics can proceed in one of two ways: passively through monitoring of emitted waves, or actively by monitoring the reflection or transmission of pulses emitted by test equipment:

- Passively, acoustic monitoring is mainly applied to active mechanical and electromechanical systems such as actuators and valves, but is also applied to static equipment such as piping. Examples of major systems in nuclear power plants include reactor vessels and piping, feedwater systems, transformers, steam lines and coolant loops. Both the sonic and ultrasonic ranges are used to detect changes in condition and degradation. (M-2 in Appendix A)
- Actively, ultrasound test is performed with very short ultrasonic pulse-waves with frequencies ranging from 0.1-15 MHz and occasionally up to 50 MHz. These are directed into materials to detect and characterize internal flaws. It is mainly applied to passive equipment/structures. (M-3 in Appendix A)

3.8 Targeted Micro/Macroscopic Measurements

The techniques included under this heading are based on a variety of very specialized measurements and are designed for a very specific type of equipment. Their common property is that they do not fit well into any of the categories identified above. Of interest are the following methods:

- Molecular test equipment applied to CMOS ICs is based on designing microscopic sensors into the IC. These are based on carbon nanotube technology and are able to sense voltage, currents and certain chemical changes which indicate progression to failure. (D-17 in Appendix A)
- Sensor diagnostics: through multi-level flow modeling (MLM) sensor failures can be detected. (D-23 in Appendix A)

- Line Resistance Analysis (LIRA) is applied to cables to detect small changes of wire electric parameters, specifically the insulation permittivity, which is a significant indicator for the condition of the cable state. Tiny insulation cracks can be detected. (H-3 in Appendix A)
- Circuit Voltage Analysis is applied to small circuits. Measuring points are designed into the die based on failure mode analysis. (H-7 in Appendix A)
- Tribology covers multiple measurement types and sensor technologies to identify and quantify contaminants in the fluids contained in moving/rotating equipment. These can be indicative of damage, or conditions leading to damage. (H-12 in Appendix A)
- Coil Current Monitoring Systems (CCMS) are designed to monitor control rod driving system (CRDS) and control element driving mechanism controls (CEDMC). They sample currents at very high frequency and can detect wave form mismatch patterns that are indicative of a variety of faults in these systems. (M-5 in Appendix A)
- Neutron Noise Monitoring is mainly used for performance monitoring but can diagnose a variety of structural faults in core internals, control rods, fuel channels and detector tubes. (M-7 in Appendix A)
- Channel mismatch detection of resolver position sensors: voltage measurements can indicate faults in the windings for this type of sensor. (M-9 in Appendix A)

4 Example Applications of AD&P Methods and Techniques

4.1 Introduction

This chapter discusses five examples of AD&P applications. The examples detailed here are categorized as either

- Model-driven
- Data-based or
- Hybrid

Essential differences between the categories are shown in Table 4-1 and are demonstrated in the following subsections. This categorization refers to the methods used to establish a failure diagnosis based on measurement/tests Model-based algorithms rely on a quantitatively defined relationship between failure modes (or equipment states in general) and observables. Data-driven methods are on the other end of the spectrum where observables cannot be clearly linked to equipment states. Rather the algorithms use empirical data to find patterns that provide evidence to support a diagnostic or prognostic result. The availability of historical data models is therefore essential. Despite the nomenclature, model-based methods also rely on significant amounts of data to validate the model and to estimate its parameters, and most data-driven techniques utilize models to account for external effects (temperature, vibration, output) on equipment life. The hybrid category includes examples that are neither purely model-based nor only data-driven. Rather they use some form of model, sometimes a conceptual model, and may rely on artificial intelligence to analyze measured data to generate a diagnosis or prognosis.

Four categories can be used to distinguish between levels in the equipment hierarchy: primitive (*e.g.* beam, pipe, solder joint), assembly (*e.g.* valve, diode), component (*e.g.* gear box, circuit board), and system (*e.g.* feed water, ventilation, digital storage). Equipment at the higher levels of the hierarchy usually has more failure modes than those at the lower levels. It is therefore not surprising that model-based techniques are primarily found at the primitive and assembly levels whereas hybrid and data-driven techniques are dominant at the component and system level.

The body of this chapter provides an example of each of the above categorized AD&P techniques. Because of the lack of publications on NPP applications most of the examples are taken from non-nuclear environments. A fourth example is presented in which observations currently taken in an NPP for operational purposes can be extended to serve as a basis for AD&P.

TABLE 4-1 CHARACTERISTICS OF THE THREE CATEGORIES

Model-based	Hybrid	Data-driven
	a. Diagnostics	
Measurements are linked directly to physical damage and used to support a diagnosis. Physical damage model for each failure mode can be fully expressed mathematically. Model parameters are obtained either from observation or physical principles. A model is not required to be on a microscopic level or cover entire time progression to failure. It is necessary that it directly links measurable variables with the state of the equipment.	Techniques that are neither based purely on models nor only on data. Hybrid damage model may be based on physical model with empirical parameters or a conceptual model that may cover multiple failure modes. The conceptual model presents a process that is understood but not necessarily mathematically formulated. (Tamilselvan & Wang, 2012)	Model generation is impractical either because of multiple failure modes, lack of knowledge, or inability to measure observables linked to a model. Hence, the equipment condition is observed externally, through indirect features (e. g., noise). Changes in equipment performance are used to support a diagnosis. Algorithms used to go from observables to a diagnosis are not model-based but may use artificial intelligence to link data patterns with equipment states.
	b. Prognostics	
Models used for diagnostics are propagated to End of Life (EOL) to estimate remaining useful life (RUL). Life consumption is estimated from past stresses and is propagated to expected stresses.	Models used for diagnostics are empirically propagated to EOL to estimate RUL. (Katipamula & Brambley, 2005)	RUL empirically estimated from comparison of past and current performance. The progression to failure in these approaches is estimated from statistics and pattern classification rather than a damage model (Coble et al., 2012).

Appendix A presents two taxonomies that are based on the model vs. data categorization. All AD&P techniques, including those not covered in this document (either in the examples below or in the sampling of Chapter 3), can be placed in a category within these taxonomies. This association allows a reader to gather an indication of the benefits and potential pitfalls of an associated technique. The taxonomies are backed-up with a set of descriptions of several dozen methods that are either currently in use or in varying stages of R&D.

4.2 AD&P Applied with a Model-Based Approach

4.2.1 General Attributes

The model-based terminology refers to the direct relationship between the measurements and the diagnostic/prognostic result: Diagnostic and Prognostic information is derived from measurements that are directly linked to physical models that are understood, are mathematically tractable, and their quantitative parameters can be assigned with a statistical confidence interval (either from theory or experiment). In that respect the system is fully transparent and implements the failure process described in Chapter 2.

The requirement for a *fully* transparent system can be eased. The concern is usually with the progression from some initial stage of failure to inoperable conditions. For example, there may not be a good model for the dynamics of crack initiation, but a model for crack propagation may be sufficient to provide timely prognostics. The model need not be derived directly from first principles, though it is based on a physical understanding of both the progression of failure and the physical parameters that are affected by this progression.

The technical challenges involved in applying a model-based approach include:

1. Obtaining a physical model of the failure process suitable for diagnostics and prognostics (failure here can be induced or the result of use-related wear and tear).
2. The ability to identify the quantitative changes in a set of physical properties that are affected by the progression to failure of the item. The item can be a primitive item, an assembly or component. The features in the examples presented below are operational features in the case of a valve, and neutron noise levels in the case of neutron dynamics.
3. The ability to translate the physical model to a tractable mathematical model.
4. The ability to identify, with sufficient confidence, quantitative parameters for the mathematical model based either on first principles or measurements.
5. A reliable and logistically effective definition of end of useful life for the item.

The above challenges determine what types of equipment can be diagnosed and prognosticated using a model-based approach. For instance, most realistic systems suffer from more than just several failure modes which can complicate physical models and their mathematical presentation. The model-based methodology is appropriate when one is able to clearly distinguish between wear-out and other failure mechanisms and their measurable effects.

As a result, the mathematical tools that are often common to model-based applications are statistical techniques that offer a means of determining the most likely of a known set of states (healthy or failed, and by which failure mode). These tools include

- Bayesian models applied to observations for identifying wear-out processes and their stage of progression
- Maximum Likelihood Estimation (MLE) of model parameters

- Simulation techniques (e.g. particle filters; Monte Carlo) that can be used to solve a model (such as Bayesian network), or fit parameters
- Statistical regression to estimate parameters and solve simple Bayesian models
- Neural networks for solving complex Bayesian models
- Frequency analyses such as Fast Fourier Transform applied to measured data for feature extraction and noise tracking

Measurement challenges are mostly in the area of collecting and transmitting high frequency and low amplitude signatures. Digital implementations are often a good solution to overcome these challenges.

4.2.2 Applicability to Levels in the System Hierarchy

The model-based approach addresses one failure mode at a time and is therefore most effective when applied to the lower levels in the system hierarchy. As shown in the Taxonomy in Appendix A, no example of a model-based approach could be found at the system level. Because model-based applications are often very closely linked to the physical model there is much variation between one application and another. This is illustrated by comparing the example of section 4.2.3 with the example of section 4.5.

4.2.3 Model-based AD&P applied to a Pneumatic Valve

An example of a model-based application for a component is a pneumatically operated valve for controlling fluid flow for the Space Shuttle. This application has been selected because of the detail with which each step of the methodology has been explained. A schematic diagram of the valve is shown in Figure 4.1 (Daigle & Goeble, 2011). The valve is open as long as the force of the air at the bottom pneumatic port is greater than the combined force due to the spring and the air at the top pneumatic port.

A detailed mathematical model is developed for the normal case as well as for each of the following five wear-out mechanisms:

- Friction between the moving element and the housing
- Reduction in the spring force
- Internal leakage (around the piston)
- External leakage from the top chamber
- External leakage from the bottom chamber.

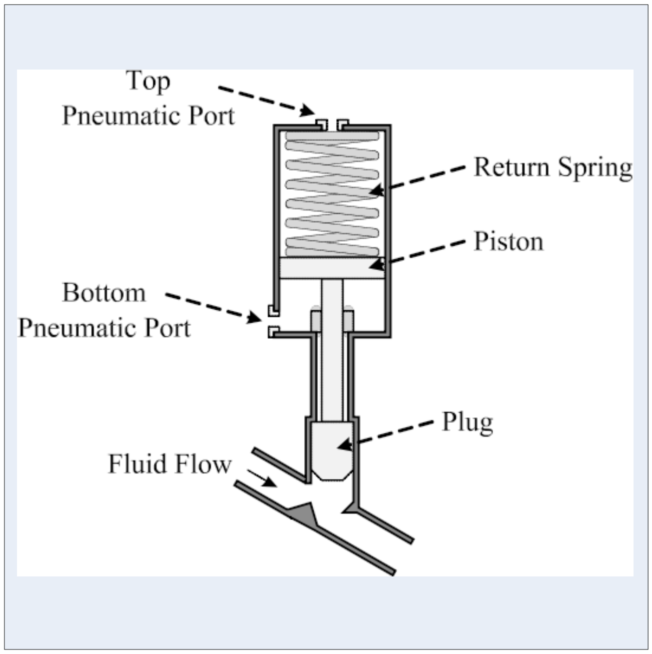

FIGURE 4-1 PNEUMATIC VALVE

The separate damage models are developed because the degree of wear-out (damage estimation) is more easily determined when a comparison between the normal state and a damaged state can be made, rather than relying exclusively on deviation from a normal state. The end of life (failed) state is defined in all but one of the wear-out mechanisms as open or close time in excess of 15 seconds, and this criterion is acknowledged as being empirical. The way in which the end of life state is approached depends on the damage mechanisms and leads to the differential diagnosis.

The exception to the 15 second criterion is the reduction in spring force. The spring is only required for closing the valve when there is a total failure of the air supply. Therefore a separate decision point is defined as the spring constant that will reliably close the valve without assist from the air supply. Once that value of spring constant had been validated, the end of life criterion was set as the spring constant dropping below it.

The overall approach for a given failure mechanism is shown in Figure 4-2. The output of damage estimation is an estimation of the current state (x_k) and the parameter vector (θ_k), given the output history ($y_{o:k}$). Examples of items in the parameter vector are piston and valve friction coefficients, rate of piston diameter reduction, and mass of gas above the piston. The prediction makes the strong assumption that the processes responsible for damage in the past will continue into the future and that the processes do not affect each other. Both damage estimation and prediction are subject to noise and several methods for estimating and filtering noise in the prediction results are given. Particle filters, a simulation technique for deducing input based on observed output are considered a particularly effective approach because they do not depend on assumption of Gaussian noise. The output of the Prediction box is the probability that the process indicates end of life (which should be low) and an estimate of the remaining useful life.

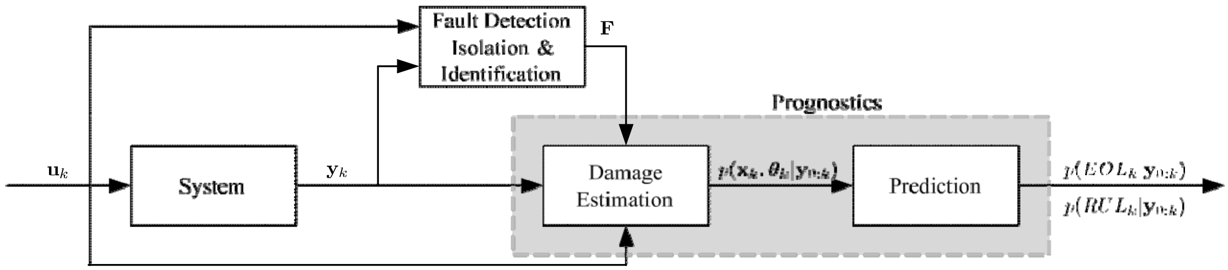

FIGURE 4-2 PROGNOSTIC ARCHITECTURE (DAIGLE & GOEBLE, 2011)

The mathematical development is rigorous and lengthy, but is based directly on the damage mechanisms and therefore it does not require artificial intelligence constructs that are used by some authors to infer causes from effects. Several limitations are recognized: the empirical definition of the end of life and the assumption that past damage processes will continue into the future. The value of this approach depends on complete knowledge of all damage mechanisms and the ability to verify that the estimated parameters of the damage process correspond to those observed in operation. Both of these conditions are satisfied when there is extensive operating experience with the item under investigation.

4.2.4 Typical Assessment Questions that Arise in the Model-Based Methodology

When a model-based analysis is used in a critical nuclear facility application, suitable assessment questions include but are not limited to:

1. What is the source and validation of the model(s)?
2. Were the model boundaries validated to ensure that operational conditions and usage are within these boundaries?
3. How were model parameters selected and validated? What is the associated confidence level?
4. Were studies with alternate models and parameters conducted? How do these compare?
5. Do the features selected for measurements cover all failure modes including potential overlap in effects?
6. At the EOL decision point, will the item still permit the next higher level to operate within its specification under all design basis events? And what is the time scale from that decision point to the time that the higher level does not operate within its specification?
7. Was simultaneous damage in several failure modes considered in the analysis? If not, is it justified?
8. If the system under observation is redundant, are the redundancy provisions (detection and switching) included in the analysis? If so, what data are available to assess the success probability for switching to an alternate? Also, how is the alternate known to be operational?
9. For redundant systems, are the components that need to be changed capable of being removed and installed under power? If not, what provisions are there to remove power?
10. Have prognostic windows been validated to be useful for time intervals of importance to NPPs and NFCFs?
11. Are there sufficient trained maintenance personnel on staff at all times?

12. What level of spares will be maintained?

4.3 AD&P Applied Using a Data-Driven Approach

4.3.1 General Attributes

The data-driven approach owes its name to its exclusive reliance on input and output measurements; particular, it does not need a model for each failure mode or even a complete enumeration of all failure modes. It does not require complete knowledge of failure processes, but relies heavily on data that is in some way (not necessarily well understood) linked to degraded item state or conditions, and material damage. The methodology is based on the fact that there are some externally observable effects that can be used to support a diagnosis and/or prognosis. The science or art of identifying these measurable features and optimizing their measurement through sensor placement and proper signal processing is based on a combination of science, experience, and trial and error. To make up for the lack of a clear link between the features and the actual conditions or state of the item, much historical data is required. The data is not used to fit a model or solve a Bayesian assumption. Rather the data is used as a basis for comparison with current measurements. Current features, feature patterns and trends are compared with stored data and trend patterns that were previously associated with an actual diagnosis or RUL. Based on this comparison a current diagnosis and/or prognosis are generated. The "comparison" is not a simple one as the multiplicity of failure modes usually implies many patterns and trends, and this task generates not an absolute result but rather an indication of the most likely current state and conditions, with a specified confidence level. The analysis usually utilizes pattern recognition, and artificial intelligence.

Because there is dependence, in the data-driven approach, on externally observed progression of damage effects to an empirically selected end of life criterion, the prognostic information is typically based on performance at a higher level in the equipment hierarchy.

The technical challenges involved in applying a data-driven approach include:

1. Identifying measurable features (effects) that are reliably linked to the damage process or conditions. This challenge includes identifying a sufficient number of such features so as to be sure that failure modes that may present similar effects but have a different progression to EOL are separable.
2. Collecting/accessing a sufficiently large database of feature patterns for statistical comparison. This is usually the most significant challenge given that there is no physical model to rely on. Moreover, in practice one usually maintains equipment in such a way that it is treated or replaced before EOL, and therefore there is little operational data showing that limit.
3. The ability to develop a pattern/trend recognition algorithm that will support a diagnosis and/or prognosis at a sufficiently early stage. This challenge can be found also in model-based applications but more so in the data-driven methodology because of the lack of transparency as to the exact relationships between the tracked features and the underlying physical process.
4. The ability to measure and analyze with sufficient accuracy the physical features that are the basis for the analysis.
5. A reliable and logistically effective definition of end of useful life for the item.

The above challenges determine what types of systems can be analyzed for diagnostics and prognostics with a purely data-driven approach. The main challenge for realistic systems is the access to sufficient historical data. This is especially true for mission critical systems that are not "allowed" to reach actual end of useful life but are replaced/maintained much earlier.

The mathematical tools that are common to data-driven applications are derived from artificial intelligence and machine learning, specifically those utilized for pattern classification:

- State Vector Machines and their variants.
- Neural Networks.
- Frequency analyses such as Fast Fourier Transform applied to measured data for feature extraction and noise separation.

Every application may have unique measurement challenges. However, measurement challenges that are common to data-driven applications are mostly in the area of collecting and transmitting high frequency and low amplitude signatures. Digital implementations are often a good solution for overcoming these challenges.

4.3.2 Applicability to Levels in the System Hierarchy

The data-driven approach has fewer a priori limitations to its use, although its implementation is at least as challenging as that of model-based applications. Data-driven applications can be found at high levels of the system hierarchy and such an example is provided below in section 4.3.3, which discusses the application of SMART to Hard Drives. However, because this methodology can deal with items with many failure modes it is also useful when approaching lower complexity items with complex degradation processes.

Data-driven analysis is most widely used for electronics because of the many failure modes that are encountered there. The data-driven approach is suitable for all levels in the equipment hierarchy.

4.3.3 Data-Driven Example for Computer Hard Disk Drives

The example of data-driven AD&P application is the SMART monitoring system for computer hard disk drives, the purpose of which is to detect indicators that warn of impending failure.

SMART is a quintessential example of the data-driven approach and it collects data for both diagnostics and prognostics. The measurements are symptomatic par excellence and their interpretation is phenomenological and does not rely on physical models of material or degradation. SMART does provide predictive information but it does not generate a RUL prediction: the monitoring system will provide an alarm that either indicates the hard drive condition is less than optimal or will send an alarm that indicates that a failure is imminent (depending on the indicator).

The predecessor to SMART was originated by IBM in 1992. PFA, the Predictive Failure Analysis, was developed and applied to 3.5 inch hard disk drives (IBM, 1992). The monitor periodically measured certain attributes (such as head-to-disk flying height) and sent a warning when a threshold was exceeded. Subsequently, computer manufacturer Compaq and disk drive manufacturers Seagate, Quantum, and Conner created IntelliSafe (Seagate, 2008). The disk's "health parameters" were measured by the disk drive and the values would be transferred to the operating system and user-space monitoring software. Each disk drive vendor could decide which parameters were to be included for monitoring, and what their thresholds should be. The unification was at the protocol level with the host.

The Compaq implementation was submitted to a Small Form Factor committee[3] for standardization in early 1995 (Compaq, 1995). Supported by IBM, Compaq's development partners Seagate, Quantum, and Conner, and by Western Digital, which did not have a failure prediction system at the time, the Committee chose IntelliSafe's approach, as the standard. The resulting jointly developed standard was named S.M.A.R.T., now usually spelled SMART.

The SMART standard described a communication protocol for an ATA (Advanced Technology Attachment) host to use for control monitoring and analysis in a hard disk drive. The standard did not specify particular metrics, measurements, or values. Currently SMART does imply a variety of specific indicators although these are not formally specified in the standard. The term is also understood to refer to protocols that are not related to ATA but are used to communicate self-monitoring metrics.

Currently all disk drive manufacturers apply SMART technology to their products. The measurements used by different manufacturers vary but they typically include variations of:

- Mechanical indicators, for example: fly height of the head above magnetic media; vibrations.
- Damage indicators, for example: ECC (Error Control Coding) circuitry on the hard drive card and soft error rates.
- Thermal indicators, for example: ambient temperatures, rate of cooling airflow.

A list of over 200 attributes can be found in ATA/ATAPI Command Set (ATA8-ACS), working draft revision 6a (current to 2008) (SMART, 2008). A sample of the first five of these is provided in Table 4-2. The table includes the attribute description, whether it is a critical attribute (which would indicate that backup should be called upon immediately), and in some cases the manufacturer that has implemented the attribute. The attribute ID follows the AT Attachment (ATA) Standard. Manufacturers are not required to adhere to this list and it should be viewed as a guide only. Of these many attributes one can find many that are very similar and may only differ in the manner in which they are quantified. The list is inclusive in that respect.

[3] The Small Form Factor committee is an ad hoc electronics industry group formed to quickly develop interoperability specifications
http://en.wikipedia.org/wiki/Small_Form_Factor_committee

TABLE 4-2 SMART ATTRIBUTES (ATA)

ID	Critical	Attribute name	Value for healthy component	Description
01	Yes	Read Error Rate	Low	Vendor specific raw value. Stores data related to the rate of hardware read errors that occurred when reading data from a disk surface. The raw value has different structure for different vendors and is often not meaningful as a decimal number.
02		Throughput Performance	High	Overall (general) throughput performance of a hard disk drive. If the value of this attribute is decreasing there is a high probability that there is a problem with the disk.
03		Spin-Up Time	Low	Average time of spindle spin up (from zero RPM to fully operational [millisecs]).
04		Start/Stop Count		A tally of spindle start/stop cycles. The spindle turns on, and hence the count is increased, both after hard disk is turned entirely off (disconnected from power source) and when the hard disk returns from sleep mode.
05	Yes	Reallocated Sectors Count	Low	Count of reallocated sectors. When the hard drive finds a read/write/verification error, it marks that sector as "reallocated" and transfers data to a special reserved area (spare area). The raw value normally represents a count of the bad sectors that have been found and remapped. Thus, the higher the attribute value, the more sectors the drive has had to reallocate. This allows a drive with bad sectors to continue operation; however, a drive which has had any reallocations at all is significantly more likely to fail in the near future. While primarily used as a metric of the life expectancy of the drive, this number also affects performance. As the count of reallocated sectors increases, the read/write speed tends to become worse because the drive head is forced to seek to the reserved area whenever a remap is accessed.

The measurements and analysis performed by SMART applications provide primarily diagnostic information together with some prediction of the remaining margins. Thresholds are proprietary to the manufacturers. Quantitative prognostics can be constructed from this information by trending, although currently this is rarely implemented.

SMART is also an example of self-test as monitoring takes place both by monitoring active hard drive activities (data retrieved by the hard drive) as well as automatic off-line scan of additional operations (all data and all sectors) during periods of drive inactivity.

The special characteristics of the data-driven approach are clearly visible in this example. The first entry in the table, read error rate, is a failure effect that can be caused by any number of failure modes, such as damage to the disk, damage to the read head, degradation of the decoding circuitry and fluctuations in the spin rate. In spite of the absence of detailed failure models the information obtained furnishes a good assessment of the health of some attributes of the disk. Together with external trending it may even indicate remaining useful life.

4.3.4 Typical Assessment Questions that Arise in the Data-Driven Methodology

When an AD&P implementation based on a data-driven approach is used in a critical NPP application, pertinent assessment questions include but are not limited to:

1. What is the source for data and how is the relation of the data to damage mechanisms validated?
2. Can site-specific challenges affect continuous data availability?
3. How were the algorithms and artificial intelligence tools used for pattern recognition chosen? Have they been used in other applications, and if so with what success?
4. Were studies with alternate algorithms and parameters conducted? How did these compare?
5. Do the features selected for measurements cover all significant failure modes including potential overlap in effects?
6. At the EOL decision point, will the item still permit the next higher level to operate within its specification under all design basis events? And what is the time scale from that decision point to the time that the higher level does not operate within its specification?
7. Was simultaneous damage in several failure modes considered in the analysis? If not, is the omission justified?
8. If the system under observation is redundant, are the redundancy provisions (detection and switching) included in the analysis? If so, what data are available to assess the success probability for switching to an alternate? Also, how is the alternate known to be operational?
9. For redundant systems, are the components that need to be changed capable of being removed and installed under power? If not, what provisions are there to remove power?
10. Have prognostic windows been validated to be useful for time intervals of importance to NPPs and NFCFs?
11. Are there sufficient trained maintainers on staff at all times?
12. What level of spares will be maintained?

4.4 Example of AD&P Using a Hybrid Approach

4.4.1 General Attributes

Real world applications are usually located somewhere between the extremes of purely model-based and purely data-driven categorization. The hybrid approach covers all applications that do not fit in the extremes. In this spectrum one finds applications that benefit from both data-driven algorithms and physical models.

In the typical situation one does not have complete physical models and measurable variables to perform a purely model-based analysis but there is also not enough historical data or good enough algorithms to use a purely data-driven analysis. In some cases hybrid analysis can include a physical model of the degradation process but there will be missing elements connecting the model to the observable load and specific degradation levels. Overcoming these challenges will require use of data-driven artificial intelligence methods. In other cases one uses the physical models to provide input to data-driven algorithms so as to enable reaching a reliable solution (for example the physical model can restrict the pattern space which is explored by the algorithm so that non-physical results are eliminated a priori, *e.g.* rolling or sliding friction). As in the model-based case, the level of degradation that constitutes end of life needs to be defined by criteria that are specific to each application.

The technical challenges to realizing a hybrid diagnostic or prognostic application include a list combined from the previous two categories (see sections 4.2.1 and 4.3.1). However not all challenges listed in purely data-driven or purely model-based methodologies are found in the hybrid methodology. Use of the hybrid methodology is often based on a requirement to eliminate some of the challenges found in the two extremes.

The RUL is usually comp uted by using the degradation model, estimates of the current degradation and of model parameters, and the defined end of life criterion.

4.4.2 Applicability to Levels in the System Hierarchy

The hybrid approach can be used at all levels of the system hierarchy, from primitive to system. The example in section 4.4.3 describes a hybrid application at an intermediate level.

4.4.3 Hybrid Approach for Rotating Element

The vibration analysis of rotating elements[4] will be used as an example. The method detailed here is the application of vibration analysis to a rolling element bearing (Harris, 2000) an example of which is shown in Figure 4-3

[4] H-4 in Appendix A

Vibration may be measured using displacement sensors, velocity sensors or accelerometers, with the last being the most common. Broadband measurement, which can range from 10-10,000Hz, will identify defects through high values of the peak/RMS ratio (Crest Factor); severe defects are indicated by high-level of RMS vibration (Lacey, 2008). The actual range that is monitored depends on the specific geometry of the bearing, as the frequency depends on the location and type of defect. In general the broad band measurement detects defects only in their advanced stage. More sensitive detection is possible by concentrating on narrower frequency bands as will be described below. Researchers in industry and academia have utilized many algorithms and features for pattern recognition (machine learning) both for diagnostics and prognostics (Porotsky & Bluvband, 2012).

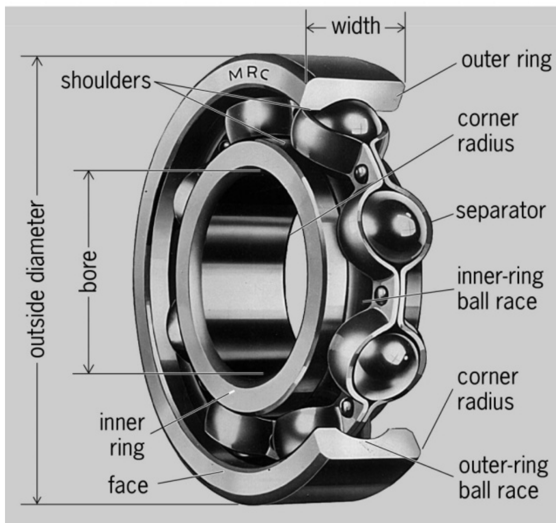

FIGURE 4-3 PARTS OF ROLLING ELEMENT BEARING[5]

At present the following sensor types are being utilized:

- Airborne Ultrasound: dB readings are used to detect high frequency acoustic emission.
- Shock Pulse Method (SPM) developed in the 60's relies on a sensor that resonates at a specific high frequency. This method can be used to detect the high frequency noise developing in the very early stages of damage when brief, random, metal-on-metal contact create shocks through the bearing metal. Analysis can provide information on the type and severity of damage. This sensor is used to specifically detect the onset of vibration due to an incipient defect.
- Envelope analysis and demodulation, the spectral analysis that removes the low frequency noise and analyzes the remaining high frequency spikes, typically uses high frequency tri-axial accelerometers.
- PeakVue[6] which is based on rapid sampling of the sensor signal and captures the short duration stress waves also uses high frequency tri-axial accelerometers[7].

[5] Taken from (http://encyclopedia2.thefreedictionary.com/antifriction+bearing)

[6] Product Datasheet http://www.icareweb.com/ressources/pdf/products/portables/2130/CSI_2130_emerson_EN.pdf

In general the sensors of choice for most applications of vibration data collection are piezoelectric or piezo-ceramic accelerometers. The output of a tri-axial accelerometer cluster (Azima, Undated) is usually integrated directly into velocity units. The accelerometers used to measure vibration are preferably mounted directly on the bearing, as close as possible to the bearing load zone (Mobius, 2012). High frequency accelerometers are available for harsh environments, such as nuclear power plants, involving high temperatures and radiation[8].
The principal damage mechanisms can be allocated to three main parts of the bearing:

- Inner Raceway: Eccentricity, waviness, surface roughness, discrete defects
- Outer Raceway: Waviness, surface roughness, discrete defects
- Rolling Element: Diameter variations, waviness, surface roughness, discrete defects

The damage is caused by contamination, temperature and load extremes, as well as imperfect maintenance and installation. These conditions will each have their own signature vibration profile.

The main mechanism for advanced diagnostics and prognostics of bearing damage is spectral analysis of the vibrations. This permits:

- Recognition of specific frequency signatures of defects and damage
- Isolation of such signatures, in the frequency domain, from ambient machine noise that is due to other machine components (e.g. electric motors, gears, belts, hydraulics, structural resonances etc.)

Poor lubrication as well as surface roughness (due to either poor manufacturing processes or later damage) will eventually lead to metal on metal contact which sends shock waves through the bearing. This leads to broadband noise at very high frequencies. As the roughness increases or lubrication decreases the noise becomes more significant and moves to somewhat lower frequencies. Eventually this type of damage will result in localized defects that generate noise spikes with well-defined frequencies depending on the location of the defect. There are guides for allowable vibration values[9]. These are primarily useful for basic alarms for a condition based maintenance (CBM) program.

More specific narrowband analysis is applied to spectral information obtained usually by Fast Fourier Transform (FFT) which translates the time domain vibration amplitudes to an amplitude vs. frequency plot.

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[7]Product Datasheet http://www2.emersonprocess.com/siteadmincenter/PM%20Asset%20Optimization%20Documents/ProductDataSheets/2130_ds_txtriaxialacce.pdf

[8] For a commercial example see http://www.bksv.com/Products/transducers/vibration/accelerometers/accelerometers/8347C.aspx

[9] For example see charts at http://www.usedvibration.com/vibration_analysis_severity_charts.htm

There are four forcing frequencies in bearing vibration: ball pass outer race (BPFO), ball pass inner race (BPFI), ball spin (BSF) and cage or fundamental train frequency (FTF). These are determined by the number of balls/rollers and the shaft rotation speed[10]. In addition, each of the parts will have its own resonant frequencies based on shape and material. The appearance of these frequencies (and their combinations) in the frequency spectrum of the vibrations will provide diagnostic information on the type, location and severity of a defect. The severity of a defect can be assessed from the number of higher harmonics that appear as well as the "noise floor". As long as the noise floor does not exceed the normal and there are not too many harmonics the defect is not severe. As degradation progresses there will be more harmonics visible and when the defect becomes severe the noise floor will also exceed the normal.

The following are examples of spectral analysis techniques primarily aimed at diagnosis:

Envelope spectral analysis is one of the features that can be used to isolate the effects of deteriorating parts from the surrounding noise. The "envelope", an example of which is shown in Figure 4-4, is a periodic amplitude modulation (AM) due to a budding defect that is periodically causing vibrations as surfaces come into contact. The envelope frequency and sidebands can provide us with information on the location of the incipient defect (*e.g.* outer raceway, inner raceway or rolling element). The advantage of inspecting the envelope is that it can be measured even when the actual vibration due to the still very small defect is much smaller than the overall vibration noise in the machine. In order to get the envelope information one must first filter out the low frequency vibrations. This method is termed High Frequency Resonance Technique (HFRT) or "Envelope Spectrum".

To select the part of the spectrum to be filtered the Spectral Kurtosis (Sawalhi & Randall, 2004) technique can be employed. Spectral Kurtosis (SK) is a statistical parameter based on the fourth moment of the signal. SK will be close to zero for Gaussian noise, but large for impulsive signals. As described above, a developing fault will generate periodic impulses which are reflected in the vibration noise. SK is therefore well suited for not only finding the demodulating envelope frequency but also for identifying and filtering the parts of the signal that are most "impulsive" and reducing the background noise.

[10] For example a bearing with 22 balls/rollers with shaft rotating at 1800 RPM will have the following four forcing frequencies: BPFO=294 Hz; BPFI=366Hz; BSF=129Hz and FTF=13.35Hz

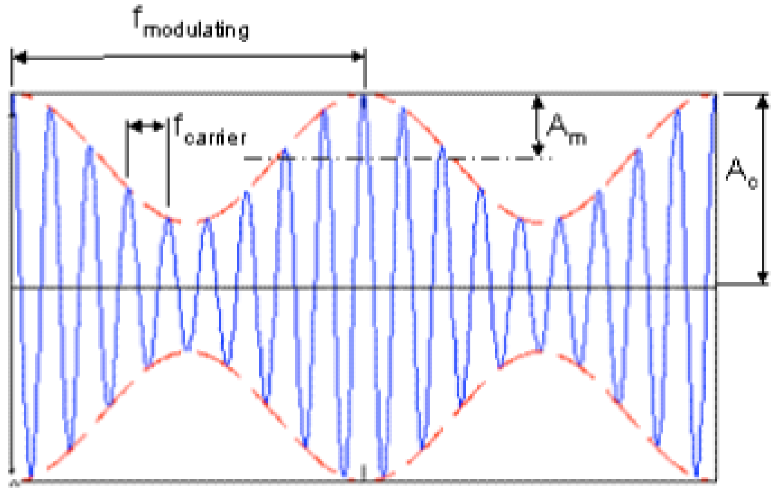

FIGURE 4-4 AMPLITUDE MODULATED SIGNAL
(http://encyclopedia2.thedictionary.com/antifriction+bearing)

Cepstrum analysis (Sawalhi, 2012) is particularly well suited for use in evaluating the patterns that emerge in the vibration spectrum of a damaged bearing as it highlights periodic spectrum structures such as the envelope frequency and accompanying sidebands.
In general the severity of a defect is judged by a combination of three metrics:

1. The number of higher harmonic peaks visible in the spectrum.
2. The amount by which each of these peaks exceeds a standard criterion.
3. The absolute amplitude of each of these peaks.

For prognostics applied to bearings, studies of the relationship of load ratings and the useful life can be used. These provide a " Life Formula for Rolling Bearings" (Lundberg & Paimgren, 1947) as well as a basis for standardizing bearing life as it depends on load (e.g. ISO 281: 1990(E) (ISO, 2007)). These "experience based methods" (Jammu & Kankar, 2011) can be useful for very general planning but neglect any stochastic behavior which is usually responsible for step-like changes in bearing condition.

Trending the severity of a defect can lead to prognostic information (Khan, 1991), (Succi, 1991), (Randall, 1985). For instance, if the severity of a defect levels off at a reasonably low damage level over a certain time period we can deduce a longer prognostic horizon. A monotonous progression will generate a warning. In general the step-like dynamics of defect progression and the resulting vibration noise, make trending relatively useless as a prognostic method.

It is worth noting that there have been attempts to develop purely physical models (i.e. model-based) that will generate estimates for RUL, for example, using stress models (YU & Harris, 2001) to estimate fatigue and life. However, these model-based efforts have very narrow application as most systems contain non-linear elements and degradation is stochastic.

For quantitative prognostics it is required to use more advanced algorithms that identify repeatable patterns that offer not only qualitative information on progression to failure but also quantitative estimates of RUL. Current efforts to implement pattern classification and machine learning algorithms for this difficult task offer various levels of success and accuracy (Jammu & Kankar, 2011). In particular the use of Artificial Neural Networks (ANN) and Fuzzy Logic has been successful at learning pre-failure patterns. However, these methods often require extremely large sets of data in order to train and validate the algorithms as they require repetition of patterns. Another complication is the correct choice of model "features" which will contain the most effective information in the data sets.

Bearings are convenient examples for AD&P using a hybrid approach, as much is known on the physical degradation processes as well as their manifestations. However, the models are complex and therefore they end up in the hybrid category rather than model-based. The following two examples illustrate how data-based information and model-based knowledge are fused to offer a viable AD&P method. These two examples take different approaches but are both based on a hybrid approach:

- Recently there have been efforts to combine both the sophisticated data and pattern analysis involved in a data-driven effort with the knowledge that comes from understanding the degradation process in a physical model. Porotsky and Bluvband (2012) have proposed a data-based method that incorporates the physical understanding that bearing degradation over time is related to the accumulated vibration noise. By evaluating accumulation functions they were able to de-noise a small data set that was a priori non-trendable and non-periodic. This method allowed them to combine data from bearings operating under very different load conditions as it cleverly normalizes the bearing history into the accumulated "integral vibration". The RUL was determined assuming a threshold for the accumulated degradation.

- Other hybrid methods make use of the physical models or experience-based models to augment models based on data-driven features in such a way that a better pattern classification process is achieved even with small data sets. Goebel *et al* propose a bearing prognostics reasoner (Goebel, et al., 2005) that integrates information from oil analysis with the information from vibration analysis to get a more accurate status of bearing damage. Their approach, designed for avionics, works in a two-mode system (in-flight and post-flight) to provide both advanced diagnostics and RUL.

4.4.4 Typical Assessment Questions that Arise in the Hybrid Methodology

When a hybrid analysis is used in a critical application, review questions will mostly follow from both the model-based and data-driven methodologies as outlined in sections 4.2.4 and 4.3.4:

1. What is the source and validation of the model(s)?
2. How were model parameters selected and validated?
3. Were studies with alternate models and parameters conducted? How do these compare?
4. At the EOL decision point, will the item still permit the next higher level to operate within its specification under all design basis events? And what is the time scale from that *decision* point to the time that the higher level does not operate within its specification?
5. What is the source for data and how is the data validated?
6. Are there any site-specific challenges that could affect continuous data availability?

7. How were the algorithms and Artificial Intelligence tools used for pattern recognition chosen? Have they been used in other applications, if so with what success? How are the algorithms validated for performance reliability? How were their reliability/repeatability tested and ensured?
8. Were studies with alternate algorithms and parameters conducted? How do these compare?
9. Do the features selected for measurements cover all failure modes including potential overlap in effects?
10. Was simultaneous damage in several failure modes considered in the analysis? If not, is it justified?
11. Are there conditions/states when the physical models can overly restrict the hybrid tools and lead to misdiagnosis?
13. If the system under observation is redundant, are the redundancy provisions (detection and switching) included in the hybrid approach? If so, what data are available to assess the success probability for switching to an alternate? Also, how is the alternate known to be operational?
14. For redundant systems, are the components that need to be changed capable of being removed and installed under power? If not, what provisions are there to remove power?
15. Are there sufficient trained maintainers on staff at all times?
16. What level of spares will be maintained?

4.5 Example of AD&P Implemented in NPP Internals

The final example in this chapter relates the details of an implementation that is model based and has been the outgrowth of technology that has been applied and useful in operation/calibration monitoring in NPPs. In that respect this is significant as it draws on existing technology that has been implemented, validated and trusted in the nuclear environment for other tasks. It is believed that this may be a common pathway to introducing other AD&P applications, a topic that is more fully discussed in the next chapter.

The example chosen under this heading is the measurement of neutron noise as an indicator of damage processes in fuel rods and structural reactor components. Neutron noise measurement is part of a larger group of methods that track and analyze reactor noise (Thie, 1963), (Williams, 1974) (others are temperature fluctuations, flow fluctuations and pressure anomalies). Physical models that link degraded states of these components with a resulting neutron noise pattern (both spatial form and amplitude) are well understood. Measurements of the noise are directly linked to geometrical aspects of degradation (e.g. rod movement or core oscillations). Therefore this is an example of a model-based application. However, the models are on a macroscopic level and do not involve the physical degradation process, only its manifestation as a failure mode at the part level. Neutron flux detectors are part of the plant instrumentation, and the attractive feature is that existing sensors can be used to provide diagnostic and prognostic information. The primary purpose of in-core neutron flux detectors is to measure the neutron flux distribution and reactor power for: in-core fuel management purposes, for control actions, and for initiating reactor protection (trip) functions in the case of an abnormal event. Coolant flow and parameters such as Moderator Temperature Coefficients can be calculated based on neutron measurement. To accomplish this, the direct current (DC) output of the detectors' current signal is measured and calibrated to indicate the neutron flux or the reactor power. The same output also contains small fluctuations (noise) that can be analyzed to collect information on the various processes taking place in the core. For example, the noise components of ex-core neutron detectors in pressurized water reactors (PWRs) can measure the vibration of the reactor vessel and the reactor vessel internals. Furthermore, through cross-correlation of neutron signals and other existing sensors such as the core exit thermocouples or the reactor vessel level sensors, the flow through the reactor can be characterized to detect flow anomalies.

Neutron noise monitoring is useful as a diagnostic for mechanical degradations and failures of the core internals and the core support structures. Based on commercial reactor service experience, pertinent laboratory data, and relevant experience from other industries, the degradation/ageing mechanisms and sources for reactor vessel internals are (Damiano & Kryter, 1990), (IAEA, 2007)

1. Embrittlement: There are two types of embrittlement. The first is irradiation embrittlement, which is caused by neutron bombardment and may affect core region internals. The second is thermal ageing embrittlement, which is a time and temperature dependent degradation mechanism and may affect the cast stainless steel parts and parts manufactured from martensitic stainless steel. The embrittlement reduces the margin on crack tolerances and design rules and affects the rate of crack propagation.
2. Fatigue: Defined as structural deterioration that occurs as a result of repeated stress/strain cycles caused by fluctuating loads and temperatures such as system cycling, thermal cycling and flow induced vibration. Fatigue may cause crack initiation and crack propagation.
3. Corrosion: The electrochemical reaction of steel with the environment that causes a detectable change which can lead to deterioration in the function of the component or structure. A variety of possible chemical and physical variables lead to a large number of types of corrosion such as: corrosion without mechanical loading (general corrosion and local corrosion attack, selective corrosion attack such as inter-granular corrosion); corrosion with mechanical loading (stress corrosion cracking, corrosion fatigue) and synergistic effects of neutron irradiation (irradiation assisted stress corrosion cracking); flow induced corrosion attack (e.g. erosion corrosion).
4. Radiation induced creep, relaxation and swelling. Neutron irradiation creates a large number of interstitials and vacancies. Diffusion controlled processes can cause these to annihilate on sinks such as dislocations, grain boundaries and surfaces. If interstitials are eliminated rapidly, the excess vacancies coalesce into voids or bubbles inside the metal leading to swelling of the structure. If a significant stress is applied, interstitials can migrate towards locations perpendicular to the applied stress creating an irradiation creep or irradiation relaxation phenomena.
5. Mechanical wear: This degradation type is broadly characterized as mechanically induced or aided degradation mechanism. Degradation from small amplitude, oscillatory motion, between continuously rubbing surfaces, is generally termed fretting. Vibration of relatively large amplitude, resulting in intermittent sliding contact between two parts, is termed sliding wear, or wear. Wear generally results from concurrent effects of vibration and corrosion. The major stressor in fretting and wear is flow induced vibration.

6. Handling: Internal structures have to be removed periodically, either partially or completely, for refueling or in-service inspection. Great care has to be exercised in the handling of these internals since some parts (pins, etc.) are easily distorted. This can cause degradation of the parts.

From the operating and maintenance experience of commercial reactors around the world, the majority of events reported about problems in internals of PWR are related to stress corrosion or fatigue failures, both with and without neutron irradiation effects as summarized in Table 4-3 (IAEA, 2007).

Although they come from the same source, damage mechanisms for BWRs are classified in a different format and in some cases different nomenclature as shown in Table 4-4 (IAEA, 2005). They include corrosion, stress corrosion cracking (SCC), inter-granular stress corrosion cracking (IGSCC), irradiation-assisted SCC (IASCC), fatigue, embrittlement, and creep and stress relaxation.

As these tables indicate, a number of damage mechanisms have been identified for each of the major reactor types. Although the number is larger than in the case of the pneumatic valve it is finite and therefore can form the basis for the techniques described in subsection 4.2. The modeling takes the form of a transfer function for the neutron flux that is based on the diffusion and scattering properties of the neutrons in the medium.

The application of noise analysis techniques in nuclear power plants started with neutron noise analysis in zero power systems and research reactors (Weinberg & Schweinler, 1949). Later applications were concerned with detecting structural vibrations (control rod vibrations), in research reactors such as the one at the Oak Ridge National Laboratory (ORNL) and the High Flux Isotope Reactor (Fry, 1971). Gradually, neutron noise methods found applications in commercial power reactors as well (Fry & Kryter, 1973), (Fry, et al., 1984). At the same time, the information content in the fluctuating part of other signals (temperature, pressure, etc.) was utilized, either alone or in combination with neutron detectors or other signals (Coble, et al., 2012).

TABLE 4-3 PWR DAMAGE MECHANISMS

		Embrittlement	Fatigue	Corrosion	Wear	Creep & Swelling	Handling
Upper Internals	Control Rods, Guide tubes						
	Guide		X		X		
	Guide tube support split pins			X			
	Thermocouple columns						X
	Core plate fuel alignment pins			X			X
Lower Internals	Baffles	X		X			
	Thermal shield fasteners, welds		X				
	Locating systems (radials key)			X			
	Instrumentation guide columns						X
	Bottom instrumentation thimble		X				

In power reactors “noise sources” such as boiling of the coolant/moderator in a BWR, or vibrations of mechanical structures in a PWR, cause the medium in which the neutrons travel and multiply to fluctuate in time and space. These neutron fluctuations have a non-Poisson character because neutrons in the core are affected simultaneously in a random manner and hence their parameters become correlated.

Usually the auto- and cross-spectral distributions (APSD and CPSD, respectively) or auto- and cross-correlation functions (ACF and CCF, respectively) of the alternating current (AC) component of the measured process signals are generated and used in the analysis of noise (Sweeney & Renier, 1984). Apart from a few cases, such as BWR instability, it is assumed that the fluctuating signals are small (typically less than 0.1% of the signal’s DC component), and linear systems theory can be used. The fluctuations in the measured signal (noise) are caused by the fluctuations of another signal (noise source or perturbation) whose effect on the noise is exerted through a physical process, described by the transfer function of the unperturbed system. This physical process is modeled by the dynamic transfer function.

TABLE 4-4 BWR DAMAGE MECHANISMS

Component	Degradation Mechanism
Core Plate	IGSCC
Core Spray Internal Piping	IGSCC
Core Spray Sparger	IGSCC
CRD Guide Tube	No incidents of cracking reported
CRD Housing	No incidents of cracking reported
In-Core Housing	IGSCC
Jet Pump	
▪ Diffuser	IGSCC
▪ Hold-down beam	IGSCC
▪ Inlet mixer	Fatigue due to improper installation
▪ Riser	IGSCC
LPCI Coupling	No incidents of cracking reported
Orificed Fuel Support	No incidents of cracking reported
Core Shroud	IGSCC/IASCC
Shroud Support	IGSCC
Top Guide	IGSCC/IASCC

If the dynamic transfer function of the unperturbed core is known, the measured neutron noise can be used to detect, identify and quantify the noise sources. If the properties of the noise source are known, these measurements can also be used to monitor changes in the state of the unperturbed core, such as reactivity coefficients and stability properties. In this way, both operational parameters in the normal state as well as changes of the reactor state to abnormal can be quantified. The occurrence of new anomalies can be detected and quantified. The methodology used to describe these stochastic processes is based on the linearized form of the Langevin technique which includes the following steps: Split up the neutron flux and the cross sections into mean values and fluctuations; neglect second order terms; subtract the static equations and eliminate the delayed neutron precursors with a temporal Fourier transform.

The following examples and descriptions of the equipment and implementations show both promise, particularly in the diagnostics area, but also limitations. Examples of anomalies/disturbances that can be identified include:

- Determining the location (radial position) of vibrating control rods in PWRs and deducing degradation of the tendons;
- Detecting and quantifying core barrel vibration properties in PWRs and deducing degradation of the stringers;

- Measuring velocity of coolant flow in PWRs and deducing structural anomalies or degradation of the pumps controlling the flow;
- Determining the position of a local thermal hydraulic instability in the core of a BWR;
- Detecting and classifying detector tube vibrations and impacting in BWRs;
- Determining two phase flow parameters in BWRs.

Implementations include both in-core measurement and ex-core measurement:

<u>In core</u>: Typically, several dozen neutron detector chains are suspended in the core. These are called Self-Powered Neutron Detector (SPND) chains or In-Core Flux Detectors (ICFDs). The signals from these detectors can be mapped to show an image of a cross section through the core. Figure 4-5 (IAEA, 2012) is an example of such a mapping generated by the PAZAR system (LIPCSEI, et al., 2009). This image shows an anomaly in the bottom right of the cross section, indicative of control rod vibration. The positions of the SPNDs are indicated with little crosses.

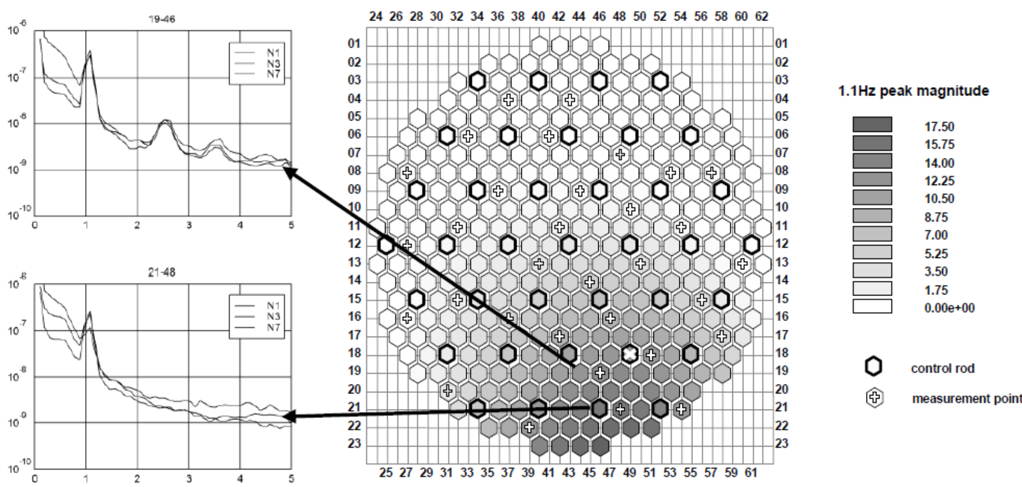

FIGURE 4-5 NOISE MAP OF CONTROL ROD VIBRATION AT 1.1HZ (THIE, 1981)

<u>Ex-core</u>: External neutron detectors can detect core vibrations: In PWRs, the core barrel is a structure hanging vertically inside the reactor pressure vessel from its top. Under certain degraded conditions the barrel might vibrate. Several modes of oscillations of the core barrel are usually encountered. The most prominent ones are the pendulum or beam-mode vibration, and the shell-mode vibration. The Eigen-frequency of the beam-mode is around 8 Hz, whereas for the shell-mode vibration the Eigen-frequency is about 20 Hz. In pre-operational test these vibrations can be measured by accelerometers, or pressure sensors, but in operational plants these sensors are usually not present and therefore such oscillations are commonly detected by ex-core neutron detectors. The vibrations cause neutron noise to be attenuated by the changes in distance to the detectors. If multiple detectors are used, both direction and amplitude of the motion can be analyzed. Pendular vibrations of the core are indicative of damage to a guide lag.

In general, reconstructing the perturbation (its location, strength and type) from the detector readings is very complicated. This process is called unfolding and requires very good models of neutron diffusion and scattering theory. The task is even more complex if the number of detectors is limited. One of the primary objectives is the detection of core-barrel vibrations and of fuel or control assembly vibrations.

A schematic illustration of an ex-core ion chamber is shown in Figure 4-6 for a typical PWR. In boiling water reactors (BWRs), average power range monitors (APRMs) and local power range monitors (LPRMs) are used to perform reactor diagnostics and to estimate the flow through the core. The APRM and LPRM signals are also used to measure the stability margin for the core in terms of a decay ratio. A detector tube with 4 surrounding fuel assemblies in a BWR core is shown in the schematic illustration Figure 4-7 (Kosaly, et al., 1981).

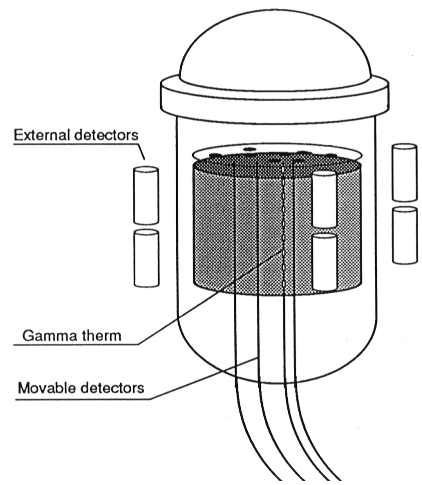

FIGURE 4-6 EX-CORE ION CHAMBERS IN A PWR

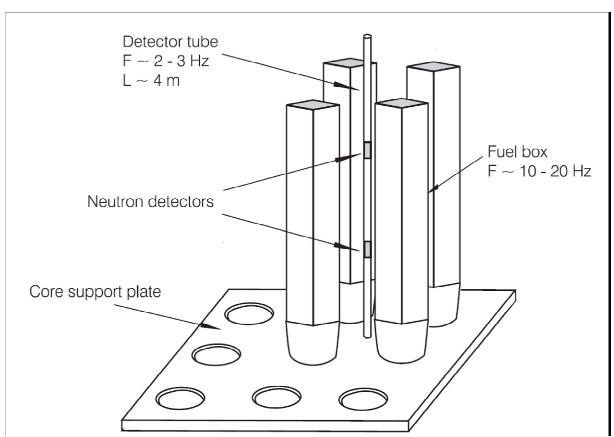

FIGURE 4-7 DETECTOR TUBE IN A BWR CORE

A classic example of the data acquisition for neutron noise measurement at ORNL is shown in Figure 4-8 (Fry, et al., 1984). Isolation of the data acquisition system from the plant equipment is required so that it will not impact reactor control system and protection systems.

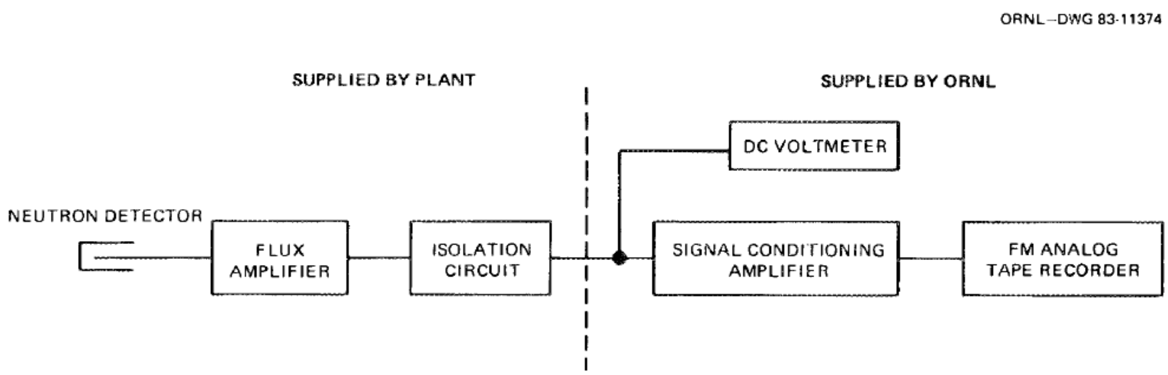

Figure 4-8 Data acquisition for Neutron Noise Measurement (Fry, et al., 1984)

The foregoing has emphasized the capabilities in neutron noise analysis for diagnostics because this is by far the area in which progress is currently being made. To exploit this methodology for prognostic purposes it is necessary to establish

- End of life (or condition based maintenance) criteria in terms of equipment characteristics and in terms of their neutron noise signatures.
- A model for the progression from a current state to the end of life point.
- Until such a model is validated, an empirical history of the approach to end of life may permit practical prognostics to be developed.

4.6 Summary

This chapter presented four representative AD&P applications and introduced a classification based on the transparency of the relationships between the equipment state and measureable variables. This categorization is useful when investigating the possible challenges in a new or reused AD&P application and offers common assessment questions and issues that should be considered in each case. The examples chosen for this chapter are cases already in use that have been tested and proven to be useful. The fourth example is of an AD&P application in NPP internals which illustrates one of the anticipated paths to introduction of AD&P into this critical domain: based on existing technology already in use for other monitoring tasks in the nuclear environment. This example is a model-based example but not a typical one: the failure mechanisms of a rod or the vibration of a vessel are not necessarily well understood, but the neutron dynamics are understood well enough to provide a transparent link to a failed or degraded state.

5 Introducing Diagnostics and Prognostics to the Nuclear Power Environment

In their basic forms, diagnostics and prognostics have existed for decades, and documentation of these engineering and analysis fields exist in many domains, from reliability through nondestructive testing and maintenance publications. Recently more focused vehicles for presenting diagnostic and prognostic tools and academic results have emerged, as well as communities that provide the environment for making R&D progress in this domain. Some of these are listed in Appendix B.

Previous chapters provided an overview to diagnostics and prognostics and highlighted techniques and concerns relevant to AD&P that involve automated and continuous monitoring. This chapter discusses the process of introducing AD&P into an operating environment. There are two pathways by which AD&P may be introduced into the nuclear power environment: deliberative and opportunistic. The latter is usually derived from an AD&P application that is already implemented in other industries, whereas the deliberative path refers to a technique that is developed “from scratch” for the specific equipment under review. The deliberative pathway is encountered when a significant gain is anticipated from an implementation of an appropriate AD&P method, although the specialized diagnostic or prognostic application has not yet been developed.

The opportunistic pathway is expected to be encountered much more frequently but the deliberative pathway will be described first because (as the name implies) it follows a defined format with individual steps that can be explained. Many of these steps will also be applicable to the opportunistic pathway but they may not be encountered in such an orderly sequence. Of course the methods and technologies used in an opportunistic pathway will have originated from a deliberative effort in another industry.

5.1 Deliberative Pathway

This pathway is entered by a decision to reduce maintenance expense or downtime for the plant as a whole or for a major section of it. In the following it is assumed that downtime can be converted into an equivalent expense and only the latter term will be used. An example of the deliberative pathway is found in the description of an effort to reduce the maintenance expense on aircraft electronic power converters (Celaya, et al., 2012).

The pathway is initiated with an expense analysis as shown in Figure 5-1. An explanation of the contributions to such an analysis was provided in section 2.4. The first step of identifying top contributors is based on a review of appropriate expense data for a recent period. Among the high scorers some may be rejected from further consideration because of legal, regulatory or organizational concerns, while others may be preferred because successful applications have been mentioned in other areas (an opportunistic element). Part 2 of this report, *Regulatory Considerations*, considers the statutory issues that affect the introduction of AD&P to nuclear facilities. These include both the requirements that must be met in order to satisfy the existing regulations as well as questions about the relevance of the regulations in a future that includes significant advances in NPP design as well as in diagnostics and prognostics.

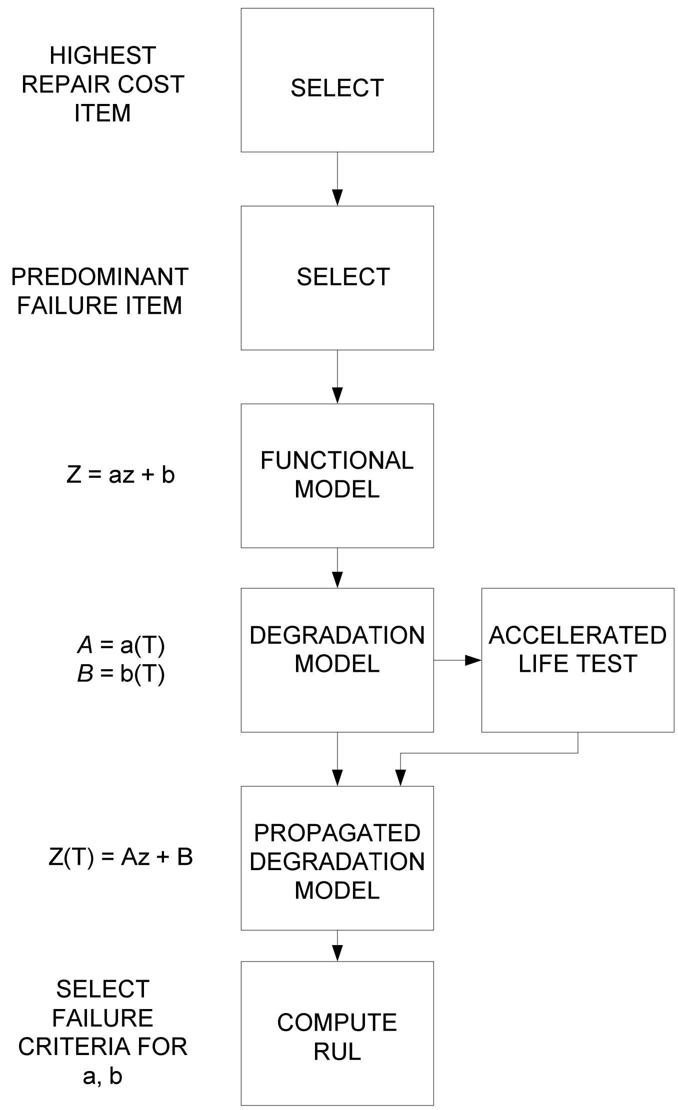

FIGURE 5-1 THE DELIBERATIVE PATHWAY

Once the highest cost items or most critical components have been selected their predominant failure modes are examined. Here again some may be declared ineligible but normally the further steps are all directed at one or several failure modes that cause the highest expense. Because of the focus on specific failure modes, the deliberative pathway tends to lead to model based or hybrid methodologies. However, there can be deliberative implementations that are purely data-driven. In such a process the focus is on the most offensive item without delving into the identification or isolation of individual failure modes. The process described in the following text and illuminated in Figure 5-1 applies to this case as well, while the details can differ substantially.

5.1.1 Example 1

In this example of aircraft electronic power converters (Celaya, et al., 2012), the first step was implied in the statement of the problem: reducing maintenance expense on aircraft electronic power converters. The power converter was recognized as the largest contributor to maintenance cost. The repair records identified failures of the low voltage (10 VDC) electrolytic capacitors to account for more of the maintenance expense than any other item.

For the selected failure modes functional models are then developed that incorporate all the a priori (usually qualitative) knowledge of how the failure modes affect the operation of the item. The equation shown to the left of the functional model block in Figure 5-1 is just an example of many possible forms that the model can take. Chapter 2 discusses in more detail what the model is based on and some examples of the use of models are discussed in Chapter 4.

For the electrolytic capacitor it is known that during use the capacitance tends to decrease and that the parasitic (unintended) series resistance tends to increase. Thus an impedance model can be constructed in which Z is the total impedance, z is the nominal capacitance, a represents the scaling factor for the decrease in capacitance and b represents the parasitic resistance. The values of a and b need not be known at this time.

Next a degradation model must be developed. Sources are the failure mode literature for the catalog item, diagnostic and prognostic literature for the general item type (in the cited example electrolytic capacitors), and in-house experience. In the equations shown to the left of the degradation model block in Figure 5-1, T represents a generalized stress-time variable that affects the associated parameters. Usually the relationship is non-linear.

Because of the uncertainties in generating the degradation model it is good practice to run an accelerated life test to validate the model. The acceleration method may itself have to be independently verified. There are other steps in this pathway where methodology or parameters need to be verified in particular circumstances and these have been omitted from the figure.

For electrolytic capacitors it was found that the most likely root cause of the degradation was loss by evaporation of electrolyte from the porous paper that separates the aluminum foil electrodes. The evaporation increases with the applied voltage, and thus the accelerated life test consists of repeated cycles of applying above rated voltage. Once this damage mechanism is verified the propagated damage model can be developed and end-of-life values of a and b can be generated.

Activities beyond this point are described in Section 5.3 since they are common to the deliberative and opportunistic pathways.

5.1.2 Example 2

A hypothetical example applicable to nuclear power and fuel cycle facilities is that of an electric motor driving a pump. The functional model, *Z,* may represent the actual output power while *z* represents the ideal output power. Factors *a* and *b* modify the ideal: *a* may represent the electric efficiency and *b* the loss of output power due to bearing friction (it will take on a negative value). A predominant damage mechanism is loss of insulation resistance in the windings. This causes leakage currents that increase the internal temperature, leading to further degradation of the insulation. The increase in winding temperature reduces power input and increases bearing friction. The motor will slow down and eventually may stall, leading to total burnout. An accelerated life test for this damage mechanism can be constructed by running the motor at elevated temperature and reduced voltage (thus causing an increase in current for a given output load).

As can be seen, the deliberative pathway can be labor intensive, may take a long time to complete and runs the risk of inconclusive test results and other uncertainties in obtaining required data. The advantage is that it can be directed at the primary area of expense. There are usually opportunistic elements that can be incorporated into the deliberative pathway to overcome some of the disadvantages.

5.2 Opportunistic Pathway

This heading describes a number of approaches by which AD&P methodologies can be introduced in the user's domain, including

- Embedded in an off-the-shelf (OTS) product.
- Available as an add-on to an OTS product.
- Available as a free-standing product.
- Described in the literature but not yet productized.
- Adaptable from a method described in the literature.

The listing is from low cost and risk and narrow focus, toward higher cost and broader target areas. Except for the first item, in which there is no selection of an AD&P methodology, the adoption process will take the form shown in Figure 5-2.

The customer becomes aware of one or more AD&P methodologies that may be suitable in the target environment. These are evaluated on the basis of anticipated return on investment or a similar criterion. If the evaluators are confident of a positive return without a prototype test they may proceed directly to procurement. Otherwise arrangements for a test will be made and the test results will determine further steps.

An example of an embedded OTS product is the S.M.A.R.T diagnostic and prognostic for disk drives (D-22 in the Appendix A). It monitors hard disk drives for many failure modes and degradation mechanisms, some with go/no go assessments and some with quantitative measurements for which the user can define end-of-life criteria.

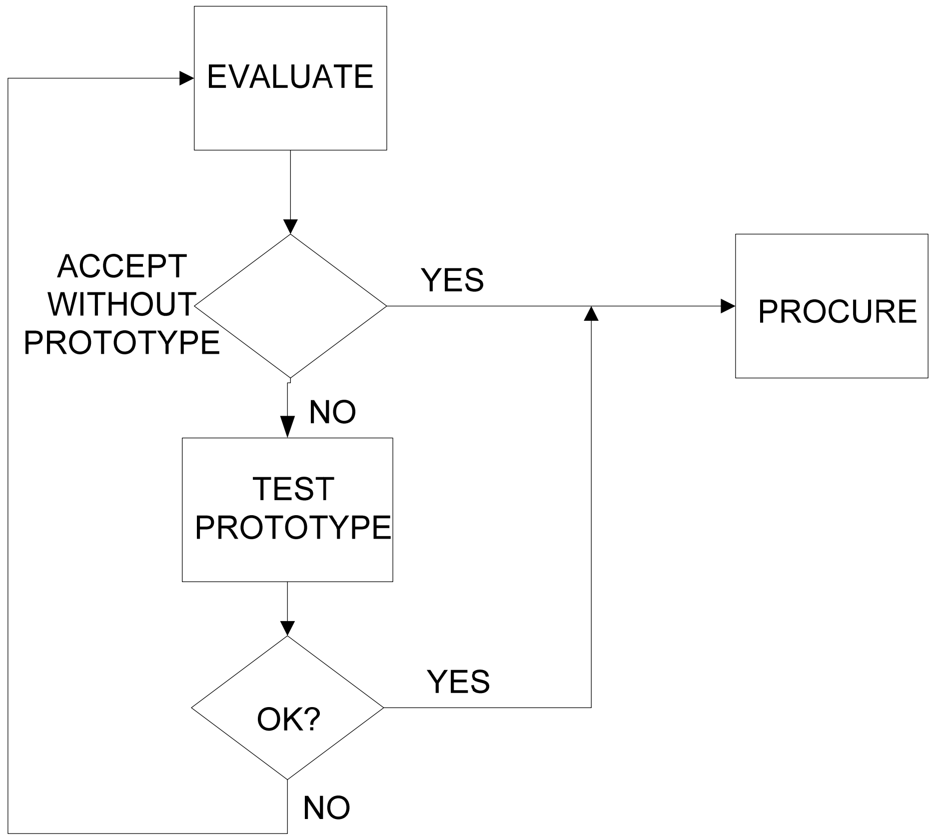

FIGURE 5-2 OPPORTUNISTIC PATHWAY FOR ADOPTION OF AD&P

An important example of a free-standing AD&P related product is the In Step PRiSM centralized performance monitoring software that was mentioned in Section 2.4.

An organization that experiences a high failure rate of low voltage electrolytic capacitors may consider the capacitance and parasitic resistance monitoring methodology described in the preceding section. Much of the model generation and verification has already been done, but accessibility of capacitors for measurement and the required instrumentation may still present obstacles.

Adapting the AD&P methodology described here for electrolytic capacitors to another electronic component this will require the development of new models and parameter estimations. But the process can still make use of the methodology described in the literature and thus avoid some of the development risk. This would constitute an example of the adaptation mentioned above.

It is anticipated that the introduction of digital instrumentation & control systems to the nuclear power industry will provide opportunistic paths to the introduction of AD&P. This introduction has already begun and it is anticipated that it will become a major part of new and renewed licensing efforts. There are actually two pathways here. Digital instrumentation can be monitored to the degree that allows for the implementation of AD&P in its own operation. Further, it offers the bandwidth and frequency capabilities required to apply advanced diagnostics, and in particular prognostics, to the equipment it controls.

The decision to adopt AD&P in the opportunistic pathway is taken within the framework of regulations. The decision process includes similar questions and issues to those confronted in the deliberative pathway.

5.3 Uses of AD&P Data

In keeping with the definitions presented in the introduction to this report, the aim of AD&P is to rationalize inspection and maintenance practices. Diagnostics establishes that an item has reached its end of useful life, and prognostics generates an estimate of remaining useful life. But there are other avenues for utilizing AD&P data and some examples will be discussed here:

- Reducing exposure to damage mechanisms.
- Improving access for repair of damage.
- Improving product design.

In the hypothetical motor example of subsection 5.1.2 the damage exposure can be reduced by not allowing heat build-up within the motor, e.g., by supplying external cooling air. Damage to disk drives can be reduced by protecting them from shock and vibration. Thinking beyond RUL may bring with it operational as well as financial benefits.

Frequently an obstacle to more productive inspections and more focused repair is the difficulty of accessing the most easily damaged components. For instance, the cited reference on the electrolytic capacitor prognostics does not mention how the capacitors mounted on a printed circuit board can be accessed to make the capacitance and resistance measurements. Usually the capacitors are part of a filter circuit in which the presence of other components may mask small changes in capacitor parameters. It is a usual maintenance practice to replace circuit boards in their entirety even though only one or a few parts may approach end of life. Ability to isolate frequently failing parts may yield large benefits.

Finally, AD&P data can and should be used to lead to improvements in product design. This can be achieved in several ways, including letting the manufacturer know of the damage experience, testing the products of competing manufacturers to determine which one is most resistant to the damage mechanism, or switching to another component type that can serve the function without exposure to the failure mechanism.

5.4 Quality and Performance Metrics

The assessment or review of a diagnostic or prognostic application necessarily requires an understanding of how its performance is measured and qualified. When presented with performance measures it is important to understand not only their numerical value but also what they represent and in some cases what they can mask. These performance metrics may be related to the top level results but may also be indicative of efficiency and quality of embedded algorithms. Although it may not be necessary for a reviewer to grasp the entire scope of the application and its performance, a background on the metrics they are most likely to be presented with is helpful for a complete picture. This section discusses some of the most common performance metrics used in diagnostics and prognostics and in fields that use similar technologies.

As the different diagnostic and prognostic methods cover very different physical measurements, as well as a variety of models and algorithms, there are also many different quality and performance metrics that can be applied to the methods (Saxena, et al., 2008), (Schwabacher, 2005), (Schwabacher & Goebel, 2007). This section discusses several metrics that have a broad application and are frequently used to qualify applications of AD&P methods.

Advanced diagnostics and prognostics rely on varying levels of statistical analysis. Hence traditionally, performance and quality evaluations borrowed standard metrics from statistics. These metrics are helpful in evaluating how well diagnostic and prognostic methods perform, but they are not always sufficient. In particular, a single measurement of a metric at a given time may be misleading. It is often useful to track over time the values of the metrics recorded at intervals. This is especially important when considering prognostics where predictions are updated continuously and should become more accurate as more data is collected. The trend over time is as important as any of the instantaneous measurements. Another issue that comes up with prognostics and is different from other statistical analyses is the time value of an RUL prediction. The quality of an early prediction is not as significant as the quality of a prediction made close to the EOL threshold. This is because the time to take action becomes shorter. The accuracy at small RUL must be significantly better than that of large RUL.

Metrics derived from statistical analysis include accuracy and precision based metrics[11] which are combinations and functions of standard statistical measurements of error and precision:

- Error: size of the deviation of the result from the actual value
- Sample Standard Deviation: measures the dispersion/spread of the error with respect to the sample mean of the error.

Different users will apply different filters and function to these metrics in order to arrive at the metric that offers them the most focused information: average error, average bias, mean absolute percentage error,

[11] Many of these metrics are in wide use in domains such as weather and finance which are concerned with the quality of predictions, and where feature classification and trend analysis have been used for decades to generate them.

correlations, mean absolute deviation, median absolute deviation, and other derivatives of these statistical measurements. A widely used derivative is that of False Positives and False Negatives which will be discussed in more detail below (Duda, et al., 2000).

All these metrics can also be assessed for their sensitivity: their response to input changes and external perturbations. The sensitivity is usually defined as the ratio of the change in the target metric to the change in the input or the size of the perturbation. A sensitivity value close to zero indicates robustness, while a value that shoots up for certain inputs indicates the method is unreliable.

It is important to remember in this context that the metric actually driving the development and implementation of advanced diagnostics and prognostics in all domains, is the Return On Investment (ROI). The significance of AD&P to operating costs was discussed previously in section 2.4. This benefit is the engine pulling this industry, and performance in terms of ROI is a significant input to operator decisions on implementations. However, it is not relevant to licensing decisions.

5.4.1 False Positives and False Negatives

Advanced diagnostic and prognostic measures are frequently implemented in an effort to avoid the manual process of removing a component to perform a visual or other inspection in order to determine an exact diagnosis. They often rely on indirect features and measurements and benefit from analyses of large sets of data. Naturally there are elements of randomness and noise in the degradation processes, the measurements, and the analysis models employed. These are unavoidable and lead to uncertainties in estimates that are used to diagnose and prognosticate. This uncertainty cannot be removed in its entirety although an effort is made to reduce it. The uncertainty is expressed in the fact that rather than having point estimates and predictions, diagnostic and prognostic algorithms will work with distributions. Figure 5-3 illustrates this uncertainty with a simple example of a diagnostic measurement. The solid curve indicates the probability of the measurement result reflecting a negative outcome and the dashed curve indicates the probability of the measurement result reflecting a positive outcome. As in medicine a "positive" result is bad news and indicates the diagnosis of a degraded condition, a negative result is good news and indicates the system is functioning well. Operators will rely on these distributions to reach a point decision on the diagnosis (positive or negative). To do so a threshold is imposed: measurements to the right of the threshold are considered positive, to the left, negative.

When the measurement is far to the right or far to the left of the threshold one can be confident with regard to its interpretation. When the measurement is in the region where the distributions overlap the interpretation may be wrong. Correct interpretations are designated as "true": True Positive (TP) means a correctly interpreted positive diagnosis; True Negative (TN) means a correctly interpreted negative diagnosis. Incorrect interpretations are designated as "false": False Positive (FP) means a positive diagnosis of a state with an actual negative value (i.e. diagnosing a problem which does not exist, a false alarm); False Negative (FN) means a negative diagnosis of a state that is actually positive (i.e. missing a diagnosis of a failure or degraded condition). These definitions are illustrated in Figure 5-3.

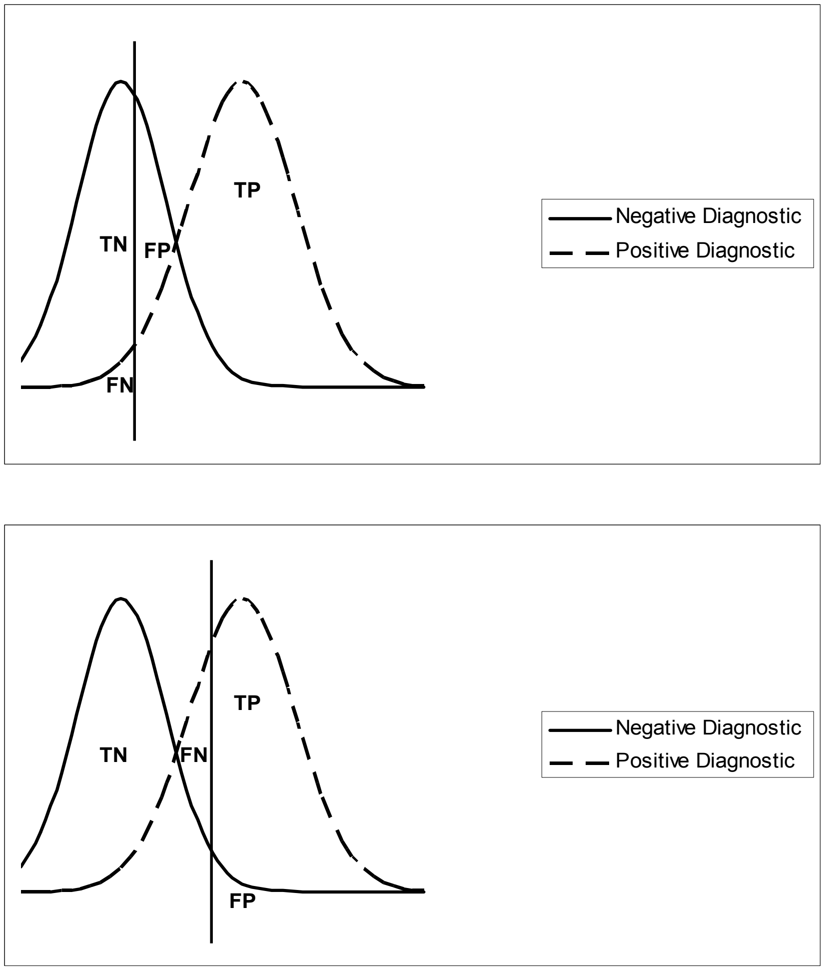

FIGURE 5-3 DISTRIBUTIONS OF DIAGNOSTIC MEASUREMENT: (TOP) A LOW THRESHOLD WILL INCUR MORE FALSE POSITIVE (FP) RESULTS; (BOTTOM) A HIGH THRESHOLD WILL INCUR MORE FALSE NEGATIVE (FN) RESULTS.

When the measurement is far to the right or far to the left of the threshold one can be confident with regard to its interpretation. When the measurement is in the region where the distributions overlap the interpretation may be wrong. Correct interpretations are designated as "true": True Positive (TP) means a correctly interpreted positive diagnosis; True Negative (TN) means a correctly interpreted negative diagnosis. Incorrect interpretations are designated as "false": False Positive (FP) means a positive diagnosis of a state with an actual negative value (i.e. diagnosing a problem which does not exist, a false alarm); False Negative (FN) means a negative diagnosis of a state that is actually positive (i.e. missing a diagnosis of a failure or degraded condition). These definitions are illustrated in Figure 5-4.

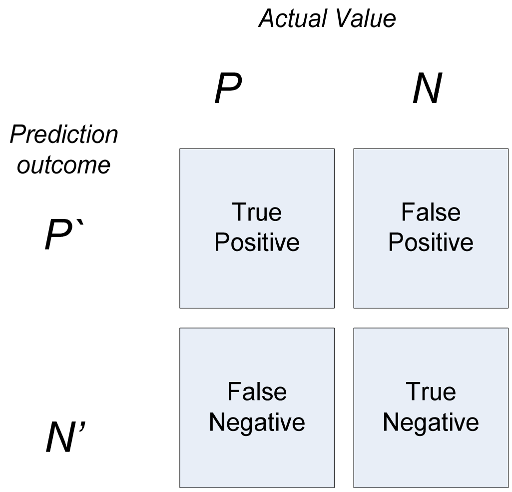

FIGURE 5-4 DEFINITIONS FOR FALSE POSITIVE AND FALSE NEGATIVE INTERPRETATIONS

False positive and false negative rates are commonly used as a metric for evaluating the performance of classifiers, and in particular diagnostic and prognostic classifiers. Although they provide a measurement of how well the classifier is performing they can be misleading. Consider a diagnostic measurement that proves to have very few FN events during test. Although this is a good indicator one must be careful to question whether there are few FN events because the classifier is exceptionally well designed, or is it because there are overall very few situations of actual positive conditions (in other words, the system is not misdiagnosing positive events, because there are hardly any such events to begin with). To overcome this type of bias, several ratios are defined that provide a more robust metric of the classifier performance:

Sensitivity or True Positive Rate: $$TPR = \frac{TP}{P} = \frac{TP}{TP + FN} \quad \text{(Eq. 5-1)}$$

Specificity or True Negative Rate**:** $$TNR = \frac{TN}{N} = \frac{TN}{TN + FP} \quad \text{(Eq.5-2)}$$

Specificity and Sensitivity are better measures of the actual success rate of the classifier – be it a diagnostic or prognostic tool. A combined graphical presentation of the TPR and the False Positive Rate (FPR=FP/(FP+TN)) is termed the Receiver Operating Characteristic (ROC) and is used to fine tune the algorithms to optimize both specificity and sensitivity. Figure 5-5 shows a typical ROC curve. The curve is a plot of the value of the TPR as one tunes the FPR from low to high. The dashed line indicates a “neutral” system with a ratio of 1. This line differentiates between good and poor classifiers: Any algorithm or tool falling beneath the diagonal would be considered a poor classifier. The solid curve in Figure 5-5 exhibits a good classifier and indicates how to optimize or "tune" it in terms of false positives and negatives (where to put the threshold).

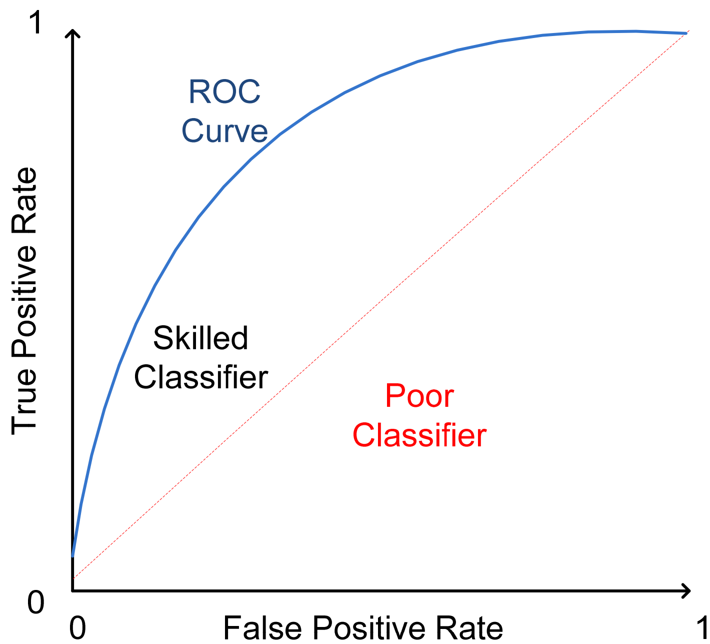

FIGURE 5-5 ROC CURVE

The area under the ROC curve can also be used as a score for the diagnostic or prognostic method. In practice tuning the algorithm to improve the position on this curve can be difficult due to lack of data as well as lack of "tuning" parameters.

5.4.2 Cost of False Positives and False Negatives

Figure 5-3 illustrates how a diagnostic tool can be tuned towards more FP or more FN by moving the vertical threshold line. It is tempting to balance the system so as to minimize the FN events at the price of more FP events: False negatives are the events where a degraded condition (which should yield a positive diagnosis) is missed by the diagnostic system. Indeed a FN can be critical as operators will not receive warning of an imminent failure that can cause catastrophic failure or complete shutdown. Decision makers will want to avoid the cost of a catastrophic FN event.

What about FP events? Although a FP event will not cause a direct failure, only increased workload or brief operational disruptions, a system biased towards a high rate of FP events will eventually lose its credibility. When experiencing multiple false alarms the human tendency is to ignore the alarms all together. At the very least, the method is ineffective and does not contribute to the ROI as it is ignored. At the very worst, an ignored TP (True Positive) has the same cost as a FN. It can be catastrophic.

If a quantitative objective can be identified, such as the plant's operating cost, this can be minimized by selecting the threshold (the vertical line in Figure 5-3) such that the expected increase in operating cost due to false negatives is equal to that due to false positives. The expected cost increase due to false negatives is the product of the probability of a false negative (the area of the negative curve to the right of the threshold) and the cost of a false negative; the expected cost increase due to a false positive is the probability of a false positive (the area of the positive curve to the left of the threshold) and the cost of a false positive. Thus, if the cost of a false positive is equal to one-tenth of that of a false negative, the threshold should be set such that the probability of a false positive is ten times that of a false negative.

5.4.3 Prognostic Metrics

As discussed above, the evaluation of prognostic tools differ somewhat from that of diagnostics because of the time element involved. The metrics applied to classifiers can be applied to prognostic tools as well, but their relevance may be limited if the progression in time is not accounted for. A FP event would be defined as an unacceptably low RUL prediction while a FN event is defined as an unacceptably high RUL prediction.

A very useful metric is that of Prognostic Horizon (PH) which quantifies how much in advance a prognostic tool or algorithm can predict RUL (within a specified accuracy) before a failure event. Consider an algorithm that provides an accurate prediction but only minutes before actual failure. As accurate as this prediction is, it is useless if it does not allow for the planning of undisruptive maintenance (or in safety-critical applications the corrective action that will prevent catastrophic failure).

A more formal metric that touches on the prognostic horizon is the α-λ performance which requires the prediction accuracy at specific times to follow a narrowing cone: α is an accuracy modifier and λ is a window modifier: a parameter that quantifies the prognostic window (RUL). The required accuracy band will narrow as RUL shrinks. In order to comply with desired α-λ specifications at all times, an algorithm must improve with time to stay within the cone.

A similar prognostic metric is that of "timeliness" which penalizes errors of later predictions with an exponential weight. Thus a statistical quality metric can be modified by a "timeliness" factor.

Other such metrics that are sensitive to the time dimension include Relative Accuracy (RA) which quantifies the accuracy relative to the actual time remaining before failure, and Convergence which quantifies how fast the performance converges for an algorithm as the End of Life (EOL) approaches.

6 The Future of AD&P in Nuclear Power Plants and Nuclear Fuel Cycle Facilities

AD&P can make a substantial contribution to the economics of the nuclear industry by helping to reduce maintenance cost and downtime, but the current use is sparse. An understanding of the failure process is essential for successful application of AD&P and therefore the first two sections of Chapter 2 have been devoted to that subject. This is followed by description of the critical role of instrumentation in providing knowledge of the state of equipment. Some instrumentation failures can lead to dangerous plant conditions and these should be considered in any AD&P efforts.

The broad range of AD&P techniques has been described in Chapter 3, and Chapter 4 covers several examples in detail in order to demonstrate research and data requirements for a successful application. Probable pathways for the introduction of AD&P have been described in Chapter 5. Appendix A contains an annotated listing of over 50 representative AD&P techniques. The evaluation of their maturity shows few that are commercially available, particularly in the prognostics area. Lest this be interpreted as a bleak outlook for AD&P a discussion of several trends is presented below that indicate much promise for the field. These trends are

- The growing emphasis on passive design features for ensuring the safety of nuclear power generation and fuel handling may increase opportunities to use AD&P without requiring regulatory approval.
- The steadily increasing capabilities of electronics and their reduced cost and physical dimensions
- The maturation of the field of Prognostics and Health Management
- The effect on future application of AD&P on the interaction of these primary trends

6.1 Passive Safety Features

The trend toward increasing use of passive safety features is exemplified in Vogtle Unit 3 in Burke County, Georgia. It is the next plant scheduled to go online in this country. The plant is a Westinghouse AP 1000 pressurized water design, for which it is claimed that it uses

- 50% fewer safety-related valves
- 35% fewer pumps
- 80% less safety related piping
- 85% less control cable
- 45% less seismic building volume

than previous pressurized water reactors (Schulz, 2006), (Bull, 2010). Similar reduced dependence on active safety features can be found in most new designs: “The greatest departure from most designs now in operation is that many incorporate passive or inherent safety features which require no active controls or operational intervention to avoid accidents in the event of malfunction, and may rely on gravity, natural convection or resistance to high temperatures.” (World Nuclear Association, 2013)

New reactor designs bring with them the opportunity to introduce new features that promise cost savings, some through use of AD&P. Economic motivation and advances in electronic capabilities (see next section) may lead to increased use of AD&P in the operational functions of NPPs and fuel cycle facilities.

6.2 Increased Electronic/Digital Capabilities

In 1965 Gordon E. Moore observed that the number of transistors on a given size chip had doubled every two years for the past ten years and that it was expected that this trend would continue (Moore, 1965). It is now almost 50 years since "Moore's Law" has been published, and its validity seems to be as firmly established as ever. This has led to vastly greater functionality, speed and precision (or resolution) of anything that can be implemented as an integrated circuit, as well as very significant reduction in cost and bulk. Many improvements in NPPs have been made possible by this trend, such as much more capable control room displays and more precise and lower cost sensors and controllers.

The self-monitoring instrumentation discussed in Subsection 2.3.1 is one obvious application of the more capable and economical electronics to AD&P. All varieties of self-test (see Section 3.3) are heavily dependent on readily available computer memory (both for selection and sequencing of test, and for the interpretation of test results). Practically all AD&P techniques in Chapter 3 depend on highly capable and affordable digital electronics. Artificial intelligence and machine learning mentioned in Chapter 4 as part of AD&P examples would not be possible without semiconductor manufacturing and packaging techniques that were introduced only in the past 20 years.

Continued progress in the development of electronics is expected to be a major contributor to the availability and affordability of free standing diagnostic and prognostic equipment and even more so to the incorporation of AD&P techniques in equipment that will be used in NPPs and fuel cycle facilities.

6.3 The Field of Prognostics & Health Management

Diagnostics have become an accepted and valued part of everyday life, e. g., the diagnostic connector in our cars and the diagnostic indications on the control panel of many household appliances. Prognostics, on the other hand, are not as well known, except in the aircraft and defense sector. This may change as additional industries and the commercial sector look for ways to reduce maintenance expenses.

One of the signposts that this movement is alive is the increasing number of prognostics and health management (PHM) conferences, publications and organizations (see Appendix B) including the development of a standard (IEEE Reliability Society, Draft P1856). The standard establishes defined equipment levels that are addressed by the prognostic applications, distinguishes between types of prognostics (model-driven, data-driven and others), emphasizes the importance of knowledge of failure modes and attempts to classify algorithms that are to be used. It also addresses economic motivation (return on investment) and implementation issues. The terminology used in this report is generally consistent with that proposed in this draft standard.

This first Part of the report serves primarily an educational function and is followed by a second Part that focuses on regulatory considerations.

Part 2: Regulatory Considerations

Chapter 7 discusses NRC regulations and their accompanying regulatory guides (RG). Also covered are two IEEE standards pertinent to AD&P IEEE Std 603 and IEEE Std 7-4.3.2. IEEE Std 603-1991 is incorporated by reference in 10CFR50.55(a)(h) and IEEE Std 7-4.3.2 is referenced in IEEE Std 603 and endorsed in RG 1.152. The chapter describes how AD&P equipment is categorized and how this affects the extent of the regulations. Since the initiative to introduce AD&P will come from the operators who are motivated by potential reductions in maintenance and monitoring costs this chapter also discusses regulations for change in Surveillance Requirements (SR) and in surveillance frequencies. Other possible changes to Technical Specifications (TS) are also discussed.

Chapter 8 focuses on industry standards. These consider the IEEE standards mentioned in Chapter 7 in more detail. Appendix B of this report provides a list of organizations dedicated to the progress in the field of AD&P and includes working groups and organizations that are developing standards and/or guidance for regulated use of AD&P. A typical process for government regulation of a new technology is through the adoption in whole or part of existing, industry standards and codes and this may be one of the avenues for coverage of AD&P.

Chapter 9 considers the path for the introduction of AD&P into NRC regulated facilities and discusses how the goals of AD&P implementations correspond with the goals of government regulation (in particular the safety regulation).

Chapter 10 presents conclusions of both parts of the report.

7 Nuclear Regulatory Commission Documents

The governing document for all regulatory requirements for NPPs and NFCFs is 10CFR (U.S. Government 10CFR). This chapter examines regulations applicable to diagnostics and prognostics. It first looks at what equipment may be subject to regulations (section 7.1) and then at the requirements pertaining to AD&P established by the regulations (section 7.2). Technical Specifications are discussed in section 7.3, and section 7.4 focuses on Surveillance Frequencies. Regulatory requirements specific to NFCFs are discussed in Section 7.5.

7.1 AD&P and Plant Equipment

10CFR50.65 is titled "Requirements for Monitoring the Effectiveness of Maintenance at Nuclear Power Plants", frequently called the Maintenance Rule. The opening sentences are abstracted below.

> *[The licensee] shall monitor the performance or condition of structures, systems, or components, against licensee-established goals, in a manner sufficient to provide reasonable assurance that these structures, systems, and components, as defined in paragraph (b) of this section, are capable of fulfilling their intended functions. These goals shall be established commensurate with safety and, where practical, take into account industrywide operating experience. When the performance or condition of a structure, system, or component does not meet established goals, appropriate corrective action shall be taken.*

The Maintenance Rule can serve as an indication (not necessarily comprehensive) of equipment that may benefit from AD&P for predictive maintenance or replacement. Plant Q-Lists, as well as all Technical Specification requirements, provide the plant-specific list of safety-related equipment subject to regulation.

An analysis of 10CFR50.65 has been issued by an industry group, the Nuclear Energy Institute, as NUMARC 93-01, Rev. 4 9 (Nuclear Energy Institute, 2010)[12] and contains a listing of equipment subject to the Maintenance Rule. That table from Section 8.2.1 is reproduced below because it provides a convenient (even if not authoritative) view of what is covered by the Maintenance Rule.

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[12] RG 1.160 rev. 3 "Monitoring the Effectiveness of Maintenance at Nuclear Power Plants" was issued in 2011 (NRC, 2012) and states that Revision 4A to this document "provides methods that are acceptable to the NRC staff for complying with the provisions of 10 CFR 50.65 with the following provisions and clarifications…" The text that follows addresses application details and allows in many cases more alternatives than the NUMARC document.

TABLE 7-1 EQUIPMENT SUBJECT TO THE MAINTENANCE RULE

Equipment Type	Example
Safety related equipment	Coolant systems, shut-down provisions, containment
Accident/transient mitigation equipment	Fire suppression system, boric acid transfer system
Emergency operation equipment	Emergency lighting and communication
Equipment that prevents a safety-related operation	Instrument air system that controls containment isolation valves, pipes that can leak into safety instrumentation
Equipment that can cause reactor shut-down	Failures in turbine-generators, multiple rod drops

It is repeatedly emphasized in the NUMARC document that industry-wide experience is to be utilized in assigning an appropriate type designation to equipment; thus, if it has been observed anywhere that a leak affected the operation of a safety-related component, that piping installation is classified as falling within the Maintenance Rule.

7.2 Requirements Impacting Diagnostics and Prognostics

Provisions of 10CFR50.55(a)(h) may affect implementation of AD&P. Excerpts from this regulation are reproduced below.

> (h) *Protection and safety systems.* (1) IEEE Std. 603-1991[13] , including the correction sheet dated January 30, 1995, which is referenced in paragraphs (h)(2) and (h)(3) of this section, is approved for incorporation by reference by the Director of the Office of the Federal Register in accordance with 5 U.S.C. 552(a) and 1 CFR Part 51.
>
> (2) *Protection systems*. For nuclear power plants with construction permits issued after January 1, 1971, but before May 13, 1999, protection systems must meet the requirements stated in either IEEE Std. 279[14], "Criteria for Protection Systems for Nuclear Power Generating Stations," or in IEEE Std. 603-1991, "Criteria for Safety Systems for Nuclear Power Generating Stations," and the correction sheet dated January 30, 1995. For nuclear power plants with construction permits issued before January 1, 1971, protection systems must be consistent with their licensing basis or may meet the requirements of IEEE Std. 603-1991 and the correction sheet dated January 30, 1995.

[13] This standard has been superseded by IEEE Std. 603-2009. A Rulemaking is in process to address differences between IEEE Std. 603-1991 and IEEE Std. 603-2009.

[14] This standard was withdrawn in 1984 (IEEE, 1971)

(3) *Safety systems*. Applications filed on or after May 13, 1999, for construction permits and operating licenses under this part, and for design approvals, design certifications, and combined licenses under part 52 of this chapter, must meet the requirements for safety systems in IEEE Std. 603–1991 and the correction sheet dated January 30, 1995.

7.2.1 Single Failure and Independence Criteria

Important concerns in connection with AD&P arise from Definitions and Explanations that precede the General Design Criteria listed in 10CFR50 Appendix A. These include the single failure criterion which in part states:

> A single failure means an occurrence which results in loss of capability of a component to perform its intended safety functions. Multiple failures resulting from a single occurrence are considered to be a single failure.

An example of how this can be pertinent is when the source of data for the safety function is shared with an AD&P component. Any failure mode within the connection to the AD&P component that can affect the data flow to the safety function will violate the single failure criterion. Some commonly used methods for providing isolation are discussed in subsection 2.3 of this report.

Independence requirements are detailed in IEEE 603-1991 which, as mentioned in the beginning of this chapter, is incorporated by reference in 10CFR50. There are several elements of the implementation and use of AD&P which can have ramifications on independence and these are dicsussed below:

Independence between redundant portions of a safety system. An issue may arrise when AD&P is used to compare independent channels in order to monitor channel health. If the AD&P is basically a single channel function it can in effect be viewed as a single channel placed in series with the multiple channel redundant system. This reduces independence and also may violate the single failure criterion. It is recommended that AD&P should not be implemented within any safety system. Safety system monitoring data should be exported and analyzed outside of safety systems.

Independence between safety systems and other systems. A possible application of an AD&P implementation serving multiple systems will also be required to maintain the independent status of any safety-system it may be serving. The derived requirement that an AD&P implementaion cannot serve both safety-related and non-safety systems may be unnecessarily restrictive as there could be instances when such an implentation may share information but maintain the independence required by safety standards. There could arise a need to include AD&P-specific regulation as it applies to this criterion in order not to unnecessarily restrict operators in the implementation of AD&P.

7.2.2 Regulatory Guide 1.153

Guidance for the application of par. 50.55a(h) is provided by RG1.153, Criteria for Safety Systems, (NRC, 1996) the pertinent provisions of which fall into two parts

- Restatement of nuclear reactor design criteria from Appendix A of 10CFR50 as a basis for requirements for safety systems
- Restatement of the applicability of IEEE Std 603 and of other industry standards that will be discussed in the next chapter.

Many of the design criteria require an assessment that the present or future strength of an SSC is at least equal to a load that may be imposed on it by a combination of environmental extremes (including earthquakes, tornadoes and tsunamis) and abnormal operating conditions. This implies that some form of diagnostic and prognostic capability may be beneficial but it does not state that it must be automated or be advanced in any form.

A set of circumstances that may impact AD&P implementations is encountered in connection with Criterion 21

> *Protection system reliability and testability:* The protection system shall be designed for high functional reliability and in-service testability commensurate with the safety functions to be performed. Redundancy and independence designed into the protection system shall be sufficient to assure that (1) no single failure results in loss of the protection function and (2) removal from service of any component or channel does not result in loss of the required minimum redundancy unless the acceptable reliability of operation of the protection system can be otherwise demonstrated. The protection system shall be designed to permit periodic testing of its functioning when the reactor is in operation, including a capability to test channels independently to determine failures and losses of redundancy that may have occurred.

In-service testability and the other features mentioned in this criterion represent a need for diagnostic capabilities. The implementation of the diagnostic capabilities is not specified, and compliance could take the form of manual record keeping.

The requirement for independence and redundancy must be maintained regardless of AD&P use. Sensitivity to single failures is interpreted to apply also to the AD&P servicing any safety system as it can result in missed latent failures or progression to failure. The particular relevance of this provision to AD&P is discussed in Section 7.2.1 above.

The one exception to the technologically neutral position relative to the means of failure detection is found in Criterion 20 that requires *automatic* operation of core protection functions:

> *Protection system functions*. The protection system shall be designed (1) to initiate automatically the operation of appropriate systems including the reactivity control

> systems, to assure that specified acceptable fuel design limits are not exceeded as a result of anticipated operational occurrences and (2) to sense accident conditions and to initiate the operation of systems and components important to safety.

The sensing and data handling required for this function are usually simple and may not need the capabilities usually associated with AD&P but do not exclude them.

Several of the criteria that deal with testing, notably General Design Criteria 37, 40, 43 and 46, contain a requirement to *permit periodic testing.* Generally the plant technical specification identifies the means for and frequency of this surveillance in the Surveillance Requirements (SR) sections. AD&P may in some cases provide a continuous monitoring capability and in others offer prognostics that permit a considerable extension of the inspection interval. Surveillance frequency is discussed in section 7.4.

In summary, neither the cited portions of 10CFR50 nor RG 1.153 were prepared with any awareness of advanced diagnostic and prognostic techniques. The provisions do not present a serious obstacle to the adoption of AD&P. Since updating of RG 1.153 is probably easier to accomplish than modification of 10CFR50 this may be an avenue for facilitating the benefits to plant safety and economics that may be achieved with the introduction of AD&P.

RG 1.160 rev. 3 "Monitoring the Effectiveness of Maintenance at Nuclear Power Plants" issued in 2011 (NRC, 2012) states the acceptance by NRC staff of compliance methods presented in NUMARC 93-01 (Nuclear Energy Institute, 2010). This statement however, does not change the conclusion that the Maintenance Rule (10CFR50.65) requires diagnostic capability but not necessarily through the use of AD&P.

7.3 Technical Specifications

Part of an NRC license authorizing the operation of a nuclear power station is the Technical Specification (TS). It establishes requirements for items such as safety limits, limiting safety system settings, limiting control settings, limiting conditions for operation, surveillance requirements, design features, and administrative controls. None of several current TS documents that were reviewed in the preparation of this report show awareness of AD&P (or its variants). This is consistent with the focus on results rather than on methodology. It is conceivable that widespread adoption of an AD&P technique may make it an acceptable method for satisfying certain criteria. The adoption will be facilitated if the technique has been defined by a professional standard such as generated by the ASME or IEEE.

Regulatory concerns arise when the introduction of an AD&P method can affect the existing surveillance requirements in a TS. An example of the introduction of alternative means to satisfying a surveillance requirement is given below from the Babcock and Wilcox TS Bases (NRR, 2012): Under the Post Accident Monitoring (PAM) Instrumentation (Section B.3.3.17) alternative monitoring is authorized in the following language:

> *"At this unit, the alternative monitoring provisions consist of the following:"* ,

and is followed by alternative Surveillance Requirements specific to these units. The particular case of alternatives to surveillance frequnecy requirements is discussed in detail in Section 7.4.
An indirect inclusion of AD&P in TS is through the Surveillance Requirements, in particular the Surveillance Frequencies. The required surveillance type and frequency are derived from the equipment failure characteristics as well as the current surveillance procedures. The improved assessment of equipment condition by AD&P is an element that will enter into this equation. In particular, it can be anticipated that implementation of AD&P may cause the plant operator, to modify (reduce) manual, periodic surveillance. The regulatory considerations of surveillance frequencies are discussed in section 7.4.

Another manner in which TS may be modified as a result of AD&P usage is through both quantitative and qualitative parameters that define various "conditions" that require action. Improved diagnostics, and in particular prognostics, could lead to more specific and reliable measures of equipment limits (for example: a requirement that control rod alignment be within a specified range of values) that will be included in a TS. The bases for these changes can be anticipated to derive from the industrial standards established by professional organizations such as ASME and IEEE.

The discussion of the benefits of AD&P to improve plant assessment earlier in this report may cause licensees to make requests to

- Safely reduce the frequency of surveillance.
- Make safe changes in other surveillance requirements that pertain to the operator's ability to keep equipment operational while performing surveillance.

If the existing TS and their regulatory bases are interpreted as "anything that is not prohibited is allowed" a gradual introduction of AD&P will not encounter significant obstacles.

7.4 Modification of Surveillance Frequencies

As discussed in the previous section, the issue of surveillance frequencies is not the only factor that can affect the introduction of AD&P but it is an important and recurring topic, and initially it may be the primary area where implementations of AD&P will interact with regulations. Surveillance frequencies are established in the Surveillance Requirements (SR) in Technical Specifications.

7.4.1 Precedents for Modification of Surveillance Frequencies

As discussed earlier in this chapter, one of the main areas in which introduction of AD&P may have regulatory ramifications is in licensee requests to change the frequency of periodic surveillance. Generally the plant Technical Specification identifies the means for and frequency of the surveillance in the Surveillance Requirements (SR) sections. Typically the frequency established in the Surveillance Requirements comes from one of the following sources:

1. 10CFR 50 (e.g. for the reactor Coolant System Pressure Isolation Valve, CFR 50.55a(g) (U. S. Nuclear Regulatory Commission, 1996)).

2. The American Society of Mechanical Engineers (ASME) code for Operation and Maintenance of NPP (ASME, 2011).
3. Regulatory Guides (e.g. for standby diesel electrical power generator Regulatory Guide 1.9 Revision 3, 1993 (NRC, 1993)).
4. Generic Letters (e.g. for standby diesel electrical power generator Generic Letter 84-15 (NRC, 1984)).
5. A "Surveillance Frequency Control Program" (see discussion below).

The last will probably initially be the preferred route because of established precedents. As AD&P becomes more ubiquitous in the industry one can anticipate that the advantages, as they relate to frequency of surveillance, will be formalized via one of the other means (1-4 above). The regulatory framework for the licensee-sponsored "Surveillance Frequency Control Program" (SFCP) is discussed below.

TSTF-425 (TSTF, 2009), is the Technical Specification Task Force transmittal that provides the basis for the modification of Technical Specifications (TS) to include the SFCP. It forms the basis for the transfer of control over surveillance frequencies to the licensees. TSTF-425 proposed the following changes to TS:

- Adding the new administrative control programs which are the Surveillance Frequency Control Program (for example Specification 5.5.20 in NUREG-1430, 1431, 1432)
- Revision of the Bases of Surveillance Requirements (SR) to include insertions that accommodate a surveillance frequency in accordance with the SFCP.

Of specific interest are the key safety principles that TSTF-425 lists as part of the Technical Analysis (Section 4.0). In the implementation of new AD&P there may be questions as to compliance with some of these principles. In particular:

Criterion 2: *"The proposed change is consistent with the defense-in-depth philosophy"* (Key Safety Criterion #2 in Section 4.0: Technical Analysis of TSTF-425).

An AD&P implementation that modifies existing design patterns (in particular those related to redundancy and manual controls) will require justification and verification that defense-in-depth is maintained.

Criterion 3: "*The proposed change maintains sufficient safety margins."* (Key Safety Criterion #3 in Section 4.0: Technical Analysis of TSTF-425).

Criterion 4: *"When proposed changes result in an increase in core damage frequency or risk, the increases should be small and consistent with the intent of the Commission's Safety Goal Policy Statement"* (Key Safety Criterion #4 in Section 4.0: Technical Analysis of TSTF-425).

Criterion 5: *"The impact of the proposed change should be monitored using performance measurement strategies."* (Key Safety Criterion #5 in Section 4.0: Technical Analysis of TSTF-425).

The principles stated above may require verification for a new AD&P implementation based on the guidance of NEI 04-10 "Risk-Informed Method for Control of Surveillance Frequencies" (Nuclear Energy Institute , 2007) (as discussed below).

7.4.2 NEI 04-10 Risk Informed Technical Specification Task Force and Regulatory Guides (1.177, 1.175, 1.174 and 1.200)

TSTF-425 emphasizes that the basis for changing a periodic surveillance frequency should be in accordance with the Nuclear Energy Institute (NEI) Risk Informed Technical Specification Task Force (RITSTF) to implement RITSTF Initiative 5b documented in NEI 04-10 (Nuclear Energy Institute, 2007). NEI 04-10 was approved by the NRC initially only as applied to BWRs, and did not include relocation of requirements to perform surveillance on a staggered test basis. However, Revision 1 of NEI 04-10 (the accession number for this revision is ML071360456) removes both these restrictions. TSTF-425 Revision 3, which is dated March 2009 applies to both BWR and PWR and allows for licensee controlled changes of frequency of testing as well as methodology: staggered or sequential. NEI 04-10 provides the acceptable methodology for applying a Probabilistic Risk Assessment (PRA) as a basis for changing a surveillance/test frequency. When applied, the resulting frequency will be placed in the list included in the SFCP.

The technical adequacy of the PRA for a risk-informed decision is addressed by NRC RG 1.200, "An Approach for Determining the Technical Adequacy of Probabilistic Risk Assessment Results for Risk-Informed Activities" (NRC, 2009). This guide can be followed when proposing a change to the SFCP according to the process defined in NEI 04-10. The NEI 04-10 process offers a qualitative route, and when the qualitative route is insufficient a quantitative route, which requires recalculating Core Damage Frequency (CDF) and Large Early Release Frequency (LERF), provide the input for the PRA. A qualitative route may be sufficient if the requests for change are minimal. NEI 04-10 and TSTF-425 require that the PRA be continuously revisited and updated. NEI 04-10 requires the review and approval by an Independent Decision-making Panel (IDP). NEI 04-10 draws on several regulatory guidance documents for safety and regulatory justification that are discussed below: RG 1.177 (NRC, 2011), RG 1.174 (NRC, 2002) and RG 1.175 (NRC, 1998).

RG 1.177 "An Approach for Plant-Specific, Risk-Informed Decision Making: Technical Specifications"

This regulatory guide describes methods acceptable to the NRC staff for assessing the nature and impact of proposed TS changes by considering engineering issues and applying risk insights. These are applicable to surveillance and test frequency requirements and are directly implementable when considering changes due to the adoption of new AD&P.

TS changes are expected to meet a set of five key principles. Of significance in the case of changes due to adoption of a new AD&P program and a change in surveillance frequency is the requirement to monitor the impact of the proposed change using performance measurement strategies. The following are directly applicable in the case of AD&P: Regulatory Position 3.1 and Maintenance Rule 10CFR50.65 discussed in Regulatory Position 3.2.

According to RG 1.177 the considerations and data requirements for a change in surveillance frequency or method (i.e. staggered or sequential) (listed in paragraph A-1.1) are based on risk measures. These are further detailed and discussed in NUREG/CR-6141 (Samanta, et al., 1994).Paragraph A-2.3.3 discusses Data Relating to Component Testing which is also determined by PRA studies. Implementation of AD&P will affect such measures as the efficiency of test or the (negative) effects of surveillance testing (e.g. introduction of plant transients).

RG 1.175 An Approach for Plant-specific, Risk-Informed Decision making: In Service Testing

The traditional requirement for all plants that In Service Testing (IST) programs are performed in compliance with the requirements of 10CFR50.55a(f) and with Section XI of the ASME Boiler and Pressure Vessel Code (ASME, 2011),is relaxed by RG 1.175 which describes an acceptable alternative approach applying risk insights from PRA to make changes to a nuclear power plant's IST program (Risk Informed In Service Testing, RI-IST). An accompanying Standard Review Plan (SRP) (NRC, 1998a) is provided to the NRC staff in reviewing RI-IST applications.

This regulatory guide provides application-specific details of a method acceptable to the NRC staff for developing RI-IST programs and supplements the information given in Regulatory Guide 1.174.

RG 1.174 An Approach for Using Probabilistic Risk Assessment in Risk-Informed Decisions on Plant-Specific Changes to the Licensing Basis

This document provides guidance on acceptable methods for utilizing PRA information together with established traditional engineering information in the development of RI-IST programs that have improved effectiveness regarding the utilization of plant resources while still maintaining acceptable levels of quality and safety. It can be used directly to implement a PRA when establishing a new AD&P program.

7.4.3 Summary of Surveillance Frequency Requirements

Where the adoption of AD&P involves a change of frequency or type of surveillance/test requirements this will require at a minimum a qualitative PRA. The PRA will take into account both the impact of a new AD&P program on safety margins, as well as the impact of changing the surveillance frequency while using the new data/information provided by this program. The licensee may use RG1.200 (NRC, 2009) to determine the adequacy of the PRA. In situations where a qualitative assessment is not deemed adequate by the IDP, a quantitative assessment is required. This includes evaluating quantitatively the impacts mentioned above on the CDF and LERF.

For the introduction of AD&P and a resulting change (reduction) in surveillance frequency the qualitative PRA may take into account:

- The nature of items requiring correction in the existing surveillance program – if the effect of these on plant safety is minimal the risk associated with a change in surveillance frequency may be acceptable.
- The frequency at which items requiring corrections have been found in the existing surveillance program – if such items have been found only rarely and if they do not have an immediate adverse effect on plant safety the risk associated with a change in surveillance frequency may be acceptable.
- The increased information content of surveillance data obtained by AD&P may more than compensate for the reduction in frequency - AD&P may yield more high frequency data and may permit more accurate comparison with previous data to evaluate trends.

7.5 Documents Specific to Nuclear Fuel Cycle Facilities

The primary objective of regulatory guidance for NFCFs is to protect public health and safety from hazards including radiological, nuclear criticality, fire and chemical. The regulatory requirements are provided in 10 CFR Part 40, “Domestic licensing of source material”, Part 70, “Domestic licensing of special nuclear material,” and Part 76, “Certification of gaseous diffusion plants.” Fuel cycle facilities perform various functions including conversion, deconversion, enrichment and fuel fabrication. Various safeguards are used for the purpose of protection from hazards such as particle removal systems (scrubbers), and maintenance of differential pressure to prevent unintentional ventilation from the facility to the outside, etc. Existing diagnostics and maintenance practices are aimed at assessing the health of these safeguards.

Material that may affect AD&P is found in NUREG 1520(Rev. 1) Standard Review Plan for the Review of a License Application for a Fuel Cycle Facility (NRC, 2010). The target of this discussion is the IROFS (Items relied on for safety) for applications regulated under 10 CFR Part 70 Subpart H, “Additional Requirements for Certain Licensees Authorized to Possess a Critical Mass of Special Nuclear Material.” Maintenance practices may remove an IROFS from service with a required shutdown of the associated process or plant. AD&P can reduce or eliminate the need for shutdown of the process or plant and may therefore be regarded as desirable.

NUREG-1718: Standard Review Plan for the Review of an Application for a Mixed Oxide (MOX) Fuel Fabrication Facility contains similar material for the specialized case of MOX fuel processing facilities.

RG 3.56 General guidance for Testing, Operating and Maintaining Emission Control Devices at Uranium Mills (NRC, 1986) adapts the Maintenance Rule to the specific environments of Uranium Mills.

RG 3.74 Guidance for Fuel Cycle Facility Change Processes (NRC, 2012a) specifies which changes require prior approval of the NRC. A particularly pertinent one is

> “Use of new processes, technologies, or control systems for which the licensee has no prior experience (see 10 CFR 70.72(c)(1)(ii)).”

Since prior experience with AD&P may not be available, this could be interpreted as guidance for obtaining prior NRC approval.

The regulatory documents pertaining to NFCFs do not add new questions or issues to the regulatory view of AD&P. AD&P may potentially benefit NFCFs with many active safety functions.

8 Industry Standards

Among the benefits of using industry standards are the provision of a framework for inputs from users, producers and public interest organizations and the participation of experts from several disciplines in the writing and review of these standards. Professional organizations, and particularly the IEEE, have mandatory review cycles during which the standard may be affirmed without changes, may be changed to respond to advances in technology or new operating experience, or may be withdrawn because there is no longer interest in the topic. An important industry standard is IEEE Std. 603, "Standard Criteria for Safety Systems in Nucclear Power Generating Stations". The 1991 version of this standard (IEEE, 1991)is invoked in 10CFR50 and is therefore a regulatory document. Rulemaking is in progress which will address the newer version of this standard: IEEE 603-2009 (IEEE, 2009). The difference between the two versions of IEEE 603 is at this time not significant for AD&P.

Also, IEEE 603 which is targeted at safety systems is only in very limited situations applicable to AD&P that monitors the condition of the safety system. AD&P becomes part of a safety system if it furnishes an input to the safety system when it is in use in an operating power plant. Under those conditions it is subject to the provisions of IEEE 603. But if it receives data from a safety system or uses data from instrumentation that also services a safety system, it can avoid being part of the safety system by following established procedures for preventing disturbances in the AD&P from propagating to the safety system. The following details amplify these observations.

IEEE 603 is discussed below in two sections:

- The body of the standard which is normative (must be adhered to via 10CFR50).
- Annex A which is informative .

Another important standard is IEEE Std. 7-4.3.2 "IEEE Standard Criteria for Digital Computers in Safety Systems of Nuclear Power Generating Stations" (IEEE, 2010) an early version of which is referenced in IEEE 603[15]; it is discussed in section 8.3 of this chapter.

8.1 Body of IEEE Std. 603

The standard addresses the power, instrumentation and control portions of safety systems; mechanical features are brought partially under the standard via interface requirements. The NRC Regulatory Guide 1.153 "Criteria for Safety Systems" (NRC, 1996) references IEEE Standard 603-1991, as well as criteria from the Maintenance Rule that have been discussed in Section 7.2 above.

Two types of provisions of IEEE 603 are particularly pertinent where AD&P is subject to the standard. The provisions also affect instrumentation that is common to AD&P and safety systems in future reactors and in the licensing extension of existing ones:

- Classification

[15] IEEE Std. 7-4.3.2-2003 is referenced in the latest version of IEEE 603.

- Design requirements.

The design requirements are important but because they were discussed in Chapter 7 above they are not revisited in this section.

The classification, that determines which criteria are applied to each equipment type, shown in Figure 8-1 below, is a matrix of *general* elements and *operational* elements of safety systems. The matrix helps to establish which criteria apply to AD&P, depending on the equipment they are serving and the particulars of their installation. The operational elements are arranged in order of criticality to the safety function, with *Other Auxiliary Features* being the least critical. Examples shown later in the standard specifically list "Built-In Test Equipment and Circuitry" as belonging to Sense and Command Features in the Other Auxiliary Features group of Operational Elements. Thus it is reasonable to assume that this classification will apply to most AD&P components.

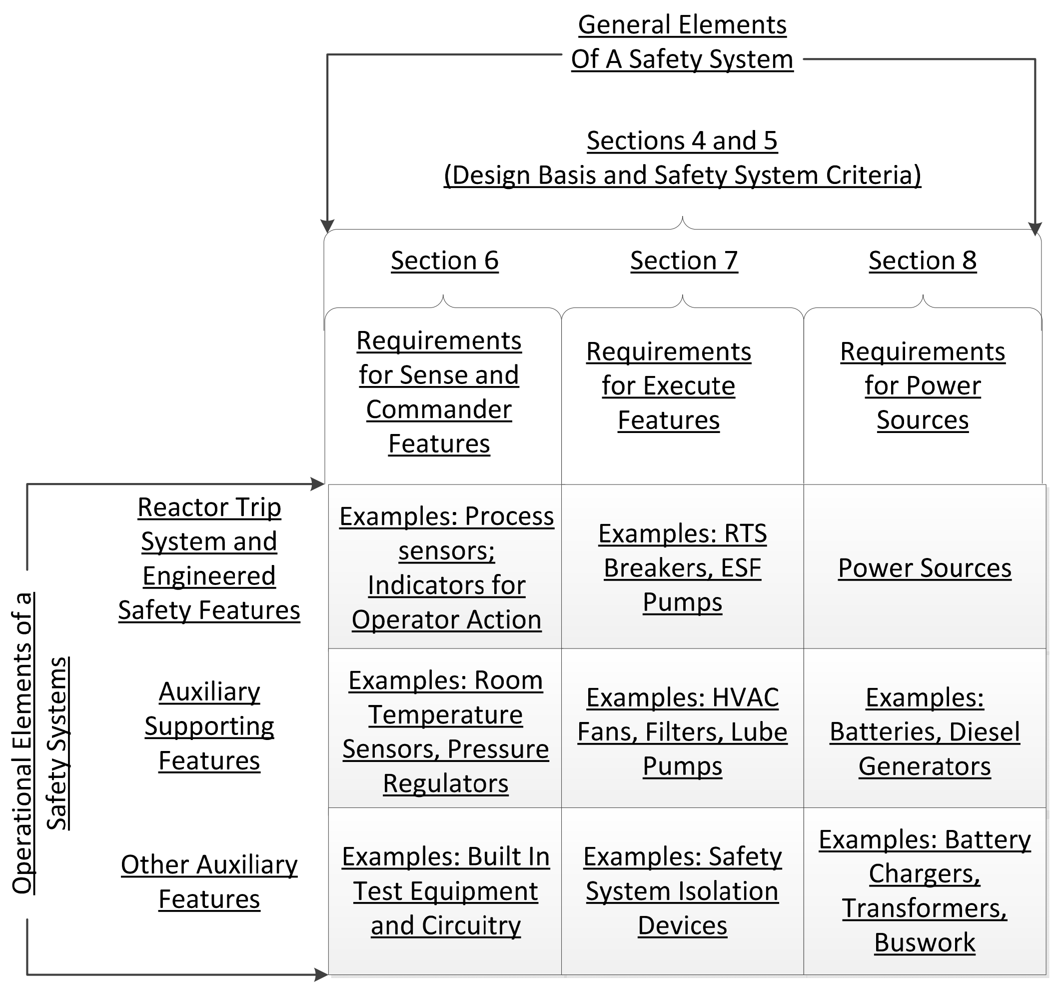

FIGURE 8-1 CLASSIFICATION IN IEEE STD. 603

The significance of this classification becomes evident in par. 5.12 of the standard:

> 5.12 Auxiliary features.
>
> Auxiliary supporting features shall meet all requirements of this standard.
>
> Other auxiliary features that perform a function that is not required for the safety systems to accomplish the safety functions, and are part of the safety systems by association (e. g., not isolated from the safety system) shall be designed to meet those criteria necessary to ensure that these components, equipment and systems do not degrade the safety systems below an acceptable level.

8.2 Annex A of IEEE Std. 603

Annex A of the standard (which is informative and therefore not a regulatory document) reaffirms that Built-In Test and other reliability related features are included in the "other auxiliary features":

> A.5 Other Auxiliary Features
>
> Included in the design of most safety systems are components and equipment whose primary function is to increase the availability or reliability of the safety system without directly performing a safety function. These components include, but are not limited to, equipment protection devices, built-in test equipment, isolation devices, etc.

The Annex further describes these features as required to

> meet only those requirements in this standard required to ensure that they do not degrade the safety system below an acceptable level. Examples of safety system criteria that such portions might not have to meet are operating bypass, maintenance bypass, and bypass indication.

AD&P can introduce common failure modes and become "part of the safety system by association" through use of a common sensor or other signal source. A short circuit or electrical noise spike in the AD&P equipment could then degrade the safety system. However, this potential threat to safety of the nuclear facility can usually be prevented through simple design features, such as the use of qualified isolation devices. This issue of connecting safety to non-safety related is not specific to AD&P and is known and well regulated.

Another way in which safety systems may become degraded due to the operation of AD&P equipment is by frequent false alarms. The degradation can be caused by placing the plant into an exception state for the purpose of investigating the cause of the alarm as well as by causing operators to question the validity of alarms. Use of multiple independent signal sources and careful design of the alarm circuitry should assure that the adverse effects on the safety system can be kept "below an acceptable level".

A further but unlikely path for introducing failure modes that are common to the target system and AD&P is by use of a common processor that can either physically malfunction or become overloaded and delay outputs that are essential to the safety of the plant. NRC guidance discourages the use of related processors for non-safety tasks and therefore this path is considered unlikely. Where such use is unavoidable all processes are to be treated as safety related. If the extension of the classification as *Other auxiliary features* from the listed example of built-in test equipment to AD&P in general is accepted, and if the simple safeguards enumerated above are adopted, IEEE Std. 603 as invoked by 10CFR50 imposes no restrictions that inhibit broad use of AD&P.

IEEE Std. 603 references a number of other standards that are listed below together with the NRC guidance documents and their significance to AD&P:

> IEEE Std. 7-4.3.2 Standard Criteria for Digital Computers in Safety Systems of Nuclear Power Generating Stations. Covered by RG1.152. This is applicable to AD&P and is discussed below.
>
> IEEE Std. 338 Standard Criteria for the Periodic Surveillance Testing of Nuclear Power Generating Station Safety. Covered by RG1.118. Applies to safety systems – not to AD&P.
>
> IEEE Std. 497 Standard Criteria for Accident Monitoring Instrumentation for Nuclear Power Generating Plants. Covered by RG1.97. Does not apply to AD&P.

8.3 Provisions of IEEE Std. 7-4.3.2 "Standard Criteria for Digital Computers in Safety Systems of Nuclear Power Generating Stations"

The applicability of this standard is endorsed in RG 1.152. Section 5.5.3 of IEEE Std. 7-4.3.2 covers fault detection and self-diagnostics. It requires self-diagnostics if faults can result in undetected partial degradation of the system. In these cases the requirement states further that the following features are required:

a) Self-diagnostics during computer system startup.
b) Periodic self-diagnostics while the computer system is operating.
c) Self-diagnostic test failure reporting.

In addition the self-diagnostic functions shall be subject to the same V&V processes as the safety system functions (safety function V&V are discussed in 5.3.3 and 5.3.4 of the standard).

As computers become embedded in safety systems (e.g., emergency core cooling systems) these provisions can be interpreted to require self-test, or more properly built-in test, of the entire system and provide a basis for a prognostics and health management function.

Other provisions of this standard pertinent to AD&P are:

Section 5.5.2 Design for test and calibration: the requirement that test and calibration functions not adversely affect the ability of the computer to perform its safety functions can be generalized to diagnostic and prognostic functions as well. In particular the standard states that "appropriate bypass of one redundant channel is not considered an adverse effect in this context." This can be interpreted as guidance to the implementation of diagnostic and prognostic functions on such a computer or system.

Section 5.6 Independence: there is a requirement for separation of safety functions from non-safety functions so that the latter cannot prevent the former from performing their intended functions. When both safety and non-safety functions reside on the same computers this can be achieved in one of two ways:

1. Barrier requirements placed on the safety functions.
2. If barrier requirements are not implemented the non-safety functions shall be developed and implemented according to the standard for safety functions.

8.4 Applications of Self-Test and Built-In Test

The requirement for self-test of digital equipment is one of the key provisions of IEEE 7-4.3.2 and it is also a requirement that can be expected to carry over into other AD&P. The technical aspects of self-test were discussed in Section 3.3 of Part 1 of this report.

The role of self-test in NPPs was addressed by Royce D. Beacom in a paper "Discerning the Need for Fault Detection and Self Diagnostics" in a 2009 meeting of the American Nuclear Society (Beacom, 2009). It states that self-testing (a) should be applied only where there is a demonstrable benefit and (b) must act and furnish information in a manner that can be assimilated by the operators under high stress conditions. In support of the first condition it elaborates:

> In most transients or events, well trained operators can quickly detect the abnormal situations and execute control functions to shut down or recover the plant through automatic responses. However, in some low-probability complex events which fall outside the scope of routine operator skill-based training and rule-based operating procedures, the operators need to use knowledge-based problem solving techniques to evaluate and predict the next possible plant states, to define tasks for control, and to recover the plant to a safe state.

In support of the second condition it cites a decision by the operator of French nuclear plants, EdF, to put a moratorium on installation of decision support features because of excessive demands on operator training for effective usage of the relevant information.

The apparent conflict between the established practice of self-test in digital systems and the established practice of depending as much as possible on plant instrumentation could be resolved if data on actual problems were available. Possible sources of this information are the experience in:

1. Development of the system that is to be licensed.
2. Non-safety/protective applications in the plant and in the fleet of the same licensee.
3. Safety/protective applications in other nuclear facilities.
4. Monitored facilities outside the nuclear industry.

The information sought is the incidence rate and manifestations of problems, the means of detection, and how the observed problems can be prevented from occurring in the future. A start for the collection of the first data item is in Interim Staff Guidance 06, e. g., V&V problem reports (Section D.4.4.2.2), Configuration Control problem reports (Section D.4.4.2.3) and Test Incident Reports (Section D.4.4.2.4).

The incentive for providing information for the second item is that it will facilitate the licensee's application for safety/protective digital functions. The means by which the information is to be collected should be acceptable to the licensing organization. The source for the third item is LERs; it may be desirable to create a separate category for those pertaining to digital systems. The information for the last item will most likely come from the instrumentation provider and a procedure should be outlined for benefits for creditable collection and dissemination.

Until such data become available both BTP 7-17 and the Beacom paper recognize that diagnosis of failures in digital components is less related to conditions monitored by the operator than in the analog case and needs self-test provisions. The following headings examine factors in failures of digital systems that support this statement.

8.4.1 Lack of correspondence between a failure and its manifestation.

One of the common causes of failure in a digital device is inversion of a memory bit, i.e., a stored 0 is converted into a 1 or vice versa. If the affected memory location is not used there will be no operational manifestation. If it is part of a data item, the subsequent read-out of this data item will yield a faulty value. But if it is part of an instruction (a component of a computer program) a wide range of manifestations is possible, some of which will result in warning messages (such as "array bound violation" or "accessing non-existing memory"), other unexpected computer operations or complete cessation of the function. One of the causes of bit inversions in semiconductors is background radiation and therefore bit inversions are for practical purposes considered inevitable.

To counter the effects of bit inversions and other memory errors, error detecting codes are employed. A typical error correcting method is to append a check bit to every eight data bits, with the check bit selected so as to make the sum of the nine bits either odd or even. In even parity, if the sum of the data bits is even, the check bit is a 0, if it is odd the check bit is a 1. More sophisticated coding schemes, including error detecting and correcting (EDAC), are frequently used. Practically all built-in test methodologies include memory checks that are based on checksums.

8.4.2 Latent Faults

As AD&P is expected to depend on software, good development, quality control and V&V practices (NRC, 2007) are essential for minimizing latent faults that may cause failures in digital systems.

Failures in digital systems can also be caused by random defects in processors, e.g. in a seldom used operations code or register, or in communications ports. The ultimate protection against latent faults and defects is defense-in-depth, multiple independent means of performing a safety function or for preventing the performance of an unsafe function.

8.4.3 Developers (particularly for software) come from a different culture than NPP engineers and operators.

In every discipline there are ground-rules that practitioners are expected to adhere to without specific instructions. Designers of NPP subsystems can be expected to be familiar with the provisions of 10CFR50 pertinent to their product but this does not necessarily hold at the level of digital instrumentation components or of AD&P. On the other hand, the specialists in digital instrumentation come with valuable craft practices that can enhance the safety and certainly reduce the cost of the installation.

Therefore specifications for digital systems, including AD&P, must be drawn very carefully and without reliance on "generally understood" provisions. Even references to professional standards may need special guidance clauses because the language of the standards may not be clear to the digital specialists.

8.4.4 Visibility of self-test performance.

Another item that is unique to digital instrumentation is that the execution of many self-test functions is not displayed to the operator. BTP 7-17 requires that the completion of tests for which surveillance credit is taken be communicated to the operator (and probably logged). It is also required that self-test functions be periodically tested and that bypassing of the functions be announced in the same manner as bypassing or inoperable status of other critical functions is announced.

8.4.5 Conclusions

Self-test and BIT of digital functions are powerful techniques that can complement other diagnostic measures to assure safety of nuclear installations. They are particularly suited for monitoring the execution of digital functions that have failure modes that are not intuitively recognized by the operators. Operational experience in NPPs or NFCFs is limited and therefore caution should be exercised if self-test and BIT are to be employed for diagnosis of events that are routinely handled by operators.

8.5 Other Industry Standards and Guides

The following are activities by professional organizations that may impact AD&P in the future.

IEEE Standards Project 1856, "(Draft) Standard Framework for Prognostics and Health Management of Electronic Systems". This is an ongoing project originated at the University of Maryland concerned with the definitions of equipment levels, prognostic methodologies and procedures for their application. It is expected that this will facilitate propagation of PHM techniques that have been successful in one application/industry to others.

In a separate effort the Prognostics and Health Management Society provides a communal meeting place and publications forum for PHM scientists and engineers. Among its many activities the society is engaged in the development and adoption of international standards.

IAEA sponsors safety related standards and although there is not one currently dedicated to AD&P, there are several existing guides/standards that are relevant to this subject and are listed in the Bibliography section of this document. Additional guidance is anticipated as there are several current international collaborations dealing with the technical issues of aging equipment. Once more these offer a field test of the newer technologies.

ASME codes are frequently used as the bases for NRC regulation (both in regulatory requirements such as in TS, and in regulatory guides). The codes build on industry-wide acceptance of testing and surveillance techniques and as AD&P are adopted by industry they will be codified by ASME.

9 Potential of AD&P to Support Plant Safety

Of central importance is also the consideration of potential benefits of AD&P in terms of plant safety, potential safety-negative impacts of AD&P or of particular methods of implementation of AD&P, and potentially unnecessary burden of existing regulations upon the full realization of AD&P. The preceding sections have primarily dealt with the prevention of safety-negative impacts and the effects of existing regulations. The focus is now shifted to the potential benefits. The technical literature recites benefits for industry in general that may be applicable to plant safety, and some of these are described in the first portion of this chapter. There is evidence of weaknesses in existing procedures (documented in LERs) that could be avoided by introduction of AD&P and these are discussed in section 9.2. The final section covers evaluation of the plant safety effects due to the operation of AD&P.

9.1 AD&P Contributions to Plant Safety Assurance

The general benefits of AD&P are discussed in Part 1 of this report. In this section benefits that pertain to regulatory considerations are discussed. Benefits of AD&P that have been reported in the literature generated by the organizations listed in Appendix B and that appear particularly applicable to safety of NPPs and nuclear fuel cycle facilities include:

- Faster identification of and response to failures, thus preventing progression to higher levels and reducing the impairment of system operation.
- Avoiding the intrusiveness of intermittent inspections.
    - Less interruption of plant operation.
    - Fewer opportunities for errors during inspection and on resumption of service.
- Specific identification of the failure type, thus facilitating speedy repair.
- Aggregation of failure or degradation reporting over a large number of units, thus permitting earlier recognition of wearout processes (facilitated by hierarchical coding of failure modes).
- Potential for reduction of human error as a cause for unidentified and unmitigated damage.

Information about achieved benefits is available through professional meetings and publications that are listed in Appendix B. These benefits may motivate licensees to consider adoption of similar practices in nuclear plants.

Examples of how AD&P can aid plant safety can be gleaned from Licensee Event Reports (LERs). Examples from a cursory review of LERs issued during the latter half of 2013 are presented below. Several contained express statements that human errors or procedural shortcomings were among the causes and these could have been avoided by AD&P. In several other cases not cited here it could be surmised that procedures were involved but it was not specifically stated.

St. Lucie #2, 3 June 2013, Docket 05000389

"…the cause was a human error in evaluating the impact to plant operation caused by the failure of the hydrogen analyzer CIV. Contributing causes included: 1) an inadequate procedure, and 2) ineffective hydrogen analyzer labeling."

AD&P may have made the recovery procedure more effective.

Susquehanna #1, 7 June 2013, Docket 05000387

"Two causal factors were identified: 1) Less than adequate life cycle management based on delay in the project to replace the EHC system with a digital replacement, 2) Less than adequate periodic maintenance to prevent oxidation and corrosion in the pressure set potentiometer."

AD&P may have detected potentiometer corrosion by measuring electrical noise.

Wolf Creek Generating Station, LER 2013-008, Docket 05000482

On September 11, 2013 the Class 1E electrical equipment air conditioning unit SGK05A was declared nonfunctional causing a plant shutdown. "The cause of the SKG05A failure was an inadequate flush and restoration of the system following actions taken to restore SGK05A in May 2013."

Wolf Creek Generating Station, LER 2013-010, Docket 05000482

On October 18, 2013 the Class 1E electrical equipment air conditioning unit SGK05A was declared nonfunctional causing a plant shutdown. "The cause of the SGK05A failure was a loss of lube oil pressure sensing of the pressure switch of the SGK05A compressor. Contaminates in the system caused the loss of lube oil pressure sensing to the pressure switch. An inadequate flush and restoration of the system in May 2013 allowed contaminates to remain in the system."

As mentioned in Part 1 of this report, AD&P can provide means for continuous sensing of lubricant contamination.

9.2 Pathways for the Introduction of AD&P

The effect of regulatory provisions on the introduction of AD&P is highly dependent on the pathway through which the new methodologies are being introduced. In the following four routes of introduction are being considered

- As part of a new reactor design.
- As a replacement of analog instrumentation by digital instrumentation.
- New into TS application as a result of favorable experience in a non-TS application.
- New without prior experience.

A licensee applying for a new plant will have solicited proposals from eligible suppliers and selected one for which favorable construction and operational data are available. The licensee and the selected supplier will be aware of applicable regulations and will discuss areas of potential problems, including those affecting AD&P, with the licensing body. The application processing and construction intervals provide an opportunity for accommodation in the regulations as well as for changes in the AD&P design or area of applicability. Considerations for the other pathways are discussed below.

9.2.1 Replacement of Analog by Digital Instrumentation

Replacement parts for existing analog instrumentation may be difficult to obtain and plant operators are then motivated to investigate digital instrumentation. As mentioned in the first part of this report, one can anticipate that AD&P will be part of the trend of increasing digital instrumentation both because there are current AD&P implementations for digital systems and because much of AD&P relies on digital capabilities.

An example of this situation that took several years to resolve resulted in granting of Amendments to Renewed Facility Operating Lincenses to Oconee Units 1, 2 and 3 for digital upgrades (NRC, 2010a). The amendments credited the self-test features of the digital instrumentation with several reductions in surveillance requirements, such as only verifying setpoints against the previously required channel functional test (SR 3.3.5.2/3.3.5.3). In another instance the requirement for a channel functional test every 92 days (without digital upgrade) is relaxed to actuation of interposing relays every 92 days and complete functional test every 18 months after the digtial upgrade is complete (SR 3.3.7.1/3.3.7.2).

The Digital Instrumentation and Controls Task Working Group #6 developed an Interim Staff Guidance (ISG) which describes the licensing process that may be used in the review of license amendment requests associated with digital I&C system modifications in operating plants originally licensed under Part 50 (NRC, 2011b). Section B of this ISG provides an overview of the scope of the review and points to all the regulation and guidance documents relevant to the licensing process of digital instrumentation including both hardware and software.

The ISG refers to IEEE 603 and where the digital system includes a processor it will be subject to IEEE Std. 7-4.3.2, in particular the self-test provisions that have been mentioned in Section 8.4. Adherence to these provisions may permit relaxation of the requirements for fixed interval testing of the processor.

A potentially adverse condition arises if processing of the digital instrument output is assigned to a central computer that also handles other safety critical data. The ISG refers to this problem and builds on existing NRC regulations and guidance (independence, defense in depth) to prevent the introduction of common mode failures via this pathway.

9.2.2 Introduction into TS Application after Use in Non-TS Application

AD&P is applicable to many plant features and procedures that are not safety related and are not covered by the plant TS. Keeping appropriate records on the operation, failure frequency and failure modes of this equipment can be an important step in facilitating regulatory approval for using this AD&P in safety related applications.

It is therefore recommended that standard procedures be developed for evaluation of AD&P equipment in non-TS applications that will form a basis for subsequent approval for use in safety-related applications. At the end of this chapter general guidelines for evaluation of AD&P equipment are presented that are partly derived from those generated for the introduction of remote monitoring. These guidelines can form the template for such a standard.

9.2.3 Introduction into TS Application without Prior Experience

Where a proposed new safety-related AD&P installation is intended to replace a conventional practice it may be desirable to operate the two in parallel for an initial observation period. Although this cannot be depended on to detect rare events it can detect conditions that can be components or precursors of rare events that occur more frequently. The parallel operation should be structured to

- Minimize changes to the existing procedure; all changes that need to be made should be documented and approved.
- Permit operation of the AD&P independent of the existing procedure; document where this is not possible.
- Obtain a complete inventory of plant equipment and state at the start of parallel operation.
- Obtain an operating and failure history of the target equipment for at least one year prior to the start of the parallel operation.

The purpose of the last two bullets is to facilitate trouble shooting and to aid in the evaluation of the AD&P. From the regulatory point of view the parallel operation serves to determine if

- AD&P detects at least all instances of non-conforming operation of the target equipment that are detected by the existing procedures.
- AD&P alerts to no more events that turn out to be nuisance alarms than the existing procedures (alarms irrelevant to the safety of the plant and of the target equipment).
- Provides safety and operational benefits that compensate for the additional complexity and maintenance obligations due to the installation of AD&P.

If the findings in all instances are favorable a reduction in the frequency[16] or intensity of the conventional procedures may be agreed to for a subsequent period of parallel operation with the aim of eventually relying exclusively on AD&P. If there are negative findings the operation of the AD&P may be changed to allow for an additional period of parallel operation or it may be abandoned.

[16] According to the regulatory procedures outlined in section 2.3 of this report

9.3 Evaluation of the Effects of AD&P Operation on Plant Safety

The evaluation of AD&P operation is intended to determine whether changes in procedures (or discontinuance) are necessary and also to form the basis of forward looking changes in regulations for further AD&P installations. Although this is a post-introduction effort it needs to be planned for as part of the introduction activities. The evaluation should address the following key issues:

- Did the adoption of AD&P achieve the intended benefits?
  - Reduction of maintenance effort.
  - Increase in plant availability.
- Did the adoption of AD&P, in spite of the analysis conducted prior to introduction, produce side effects that may impair the safety of plant operation?
  - In routine reactor operation.
  - Under design basis events.
  - By reducing the availability or effectiveness of mitigation provisions.

The plant operator is motivated and equipped to perform the evaluation of the first solid bullet but regulators will be concerned with the second solid bullet. Because the last two conditions are not likely to be observed the following describes some methodologies that can be employed for predicting the response of AD&P to rare conditions. The underlying assumption is that the response of AD&P to design basis events has been examined by simulating these conditions, and that the findings need to be confirmed by examining the response to more routinely observed status changes.

A dedicated effort can be undertaken for each installation that tracks the response to each system status change, e. g., increase or decrease in power output, outage of one of several redundant channels, testing of a Diesel generator. Baseline data for this will have to be generated for a period prior to AD&P activation and some special instrumentation may be required. For new NPPs the baseline data can be generated by simulation. The internal response of the AD&P equipment to these plant status changes can be evaluated to determine

- Whether the response to the status change is appropriate.
- Whether the response can be extrapolated to a design basis condition, and if so, whether it will alarm at the appropriate level.
- Whether the response to the status change came close to resulting in a false alarm.

In addition to a general review of the performance of AD&P, all LERs (Licensee Event Reports) for a given plant in which AD&P had been installed for a defined period (e. g., one or two years) can be examined to determine whether there was a proper AD&P response, and whether the event was due to the AD&P installation or was aggravated by it. This approach may be limited by some of the following factors:

- Detection of the connection to the AD&P installation is highly dependent on the expertise of the investigator.
- Even with expertise available it may not be possible to conclude that regulatory action regarding the AD&P installation is warranted.

- This approach cannot identify all events that were prevented due to the installation of AD&P (because the incident was no longer a reportable event).

An alternative is a statistical approach to evaluate the effects of AD&P on plant safety. This can inherently detect positive as well as negative trends but it requires (a) establishing an index for plant safety and (b) defining a procedure for measurement of that index. Neither one of these is a trivial effort.

One candidate for the index is the number of LERs with reporting requirements code 50.73 which includes most unexpected operational events. During the first half of 2013 there were approximately 50 events with that reporting code. This equates to about one report per year for each operating power reactor. Where an AD&P installation is made in only a single reactor this will require an unreasonably long time for detection of a trend. But if a given installation includes five or more plants, significant trends should be detectable within a year and more subtle ones over a two to three year period.

A combination of the detailed analysis of individual reports and the statistical approach is possible, and this may be an effective initial step.

10 Conclusions

Part 1 of this report has shown that diagnostic and prognostic procedures depend on instrumentation for knowledge of the state of the plant and that therefore the dependability of instrumentation is of concern in the application of these techniques. Measures for achieving the required dependability were presented.

Among AD&P techniques an important distinction is between model-based and data-driven procedures. In the former replacement or repair decisions are based on a mathematical model. In the latter case replacement or repair decisions are based on statistical analysis of failure effects, usually as seen in operating data. Hybrid techniques that combine elements of the model-based and data-driven approaches are also frequently encountered. In all cases parameters are determined by examination of test or operational data and the failure criterion (the threshold below which an item is declared failed) is selected empirically.

While many of the AD&P techniques described in the body of Part 1 are still in the research or early evaluation stages, a number are being successfully employed in industry and transportation, notably

- Self-test of digital systems.
- S.M.A.R.T surveillance of computer disc drives.
- Analysis of the health of rotating components by vibration signatures and contamination of lubricants.
- Detection of insulation degradation of electrical conductors.

In NPPs and NFCF a distinction must be made between applications subject to NRC license and those made at the discretion of operators. In the latter category there are several of the above techniques or their equivalents. In the licensed category only self-test could be currently found. Among techniques still in the evaluation pipeline, one that is particularly suitable for NPPs is the analysis of the high frequency component of neutron noise that is described in Section 4.5.

Part 2 of the report examines regulatory issues affecting the use of AD&P. There are no outright prescriptions or prohibitions in 10CFR or documents referenced there except the requirement for self-test in digital systems that is contained in IEEE Std. 7-4.3.2. This standard, although not incorporated by reference in 10CFR50, provides guidance in the installation of digital equipment. Restrictions affecting some types of AD&P may be encountered in guidance documents and in Technical Specifications. An example is the requirement that the connection of AD&P to the target equipment must not interfere with the operation of the latter under any conditions. Reasonable means for complying with these restrictions are usually available.

Avenues for the introduction of AD&P include

- Migration from non-licensed to licensed applications.
- Extension of the scope of self-test into full-fledged AD&P.
- Acquisition of instrumentation or equipment that includes AD&P.
- Licensing of new plants that include AD&P.

Measures to protect against unsafe conditions caused by introduction of AD&P include parallel operation of established surveillance measures with AD&P for an introductory period and monitoring AD&P for early warnings of failures to alarm or excessive false alarms. With such safeguards AD&P can be expected to make a positive contribution to the safety and operation of NPPs and NFCFs. Examples of how existing capabilities could have been deployed to prevent shut-downs of NPPs have been presented.

Appendix A Taxonomies and Their Application

An objective of this document is to provide information on the methods and technologies utilized in AD&P. This objective can benefit from a well-organized taxonomy of AD&P methods which is helpful for systematically illuminating both the challenges in this field and their possible solutions. Two taxonomies, presented in subsection A.1, build on the categorization presented in subsection 4.1 according to model-based, data-driven and hybrid techniques. Section A.2 includes descriptions of specific methods categorized according to this division. Each method is described under a separate title identified by a letter (M, H or D corresponding to model-based, hybrid, data-driven accordingly) and a sequential number. Each description includes a listing of the kinds of equipment it may target; the technology involved; failure modes it can be applied to; a discussion of the implementation and a maturity level.

In order to facilitate lookup from Chapter 3, all the entries in section A.2 are grouped according to the techniques identified in subgroups in that chapter.

A.1 Taxonomy of Technologies and Methods Used in Advanced Diagnostics and Prognostics

In the following, two taxonomy structures for AD&P techniques are represented: a research taxonomy, based on the classifications just described, and a review taxonomy, based on the types of equipment for which they are used. Both taxonomies are populated in accordance with the literature described in this appendix. The literature includes papers from recent Prognostics & Health Management (PHM) conferences or from PHM sessions of other conferences sponsored by the Institute of Electrical and Electronic Engineers (IEEE) or the American Nuclear Society (ANS). Other referenced publications are authored by experts consulted as part of this study (see Acknowledgment section of the Introduction) or recommended by these experts. No claim is made that these methodologies represent a comprehensive survey but they are believed to be representative for application to equipment/components used in current or future NPPs or NFCFs.

References that specifically address use of AD&P in NPPs are mainly in the mechanical realm (e.g. passive structures and cables, and active components such as pumps and turbines) with some in the electromechanical domain (e.g. generators and transformers). However, the general AD&P literature includes many more methods that are focused on electronic equipment. This state reflects the needs of other domains (e.g. aerospace control systems) but diagnostics and prognostics for electronic systems may be proposed for application in advanced nuclear power plants. To prepare for this future, the taxonomies detailed below include many methods applied to electronic parts, assemblies and components.

A.1.1 Research Taxonomy

The top headers of the research taxonomy shown in Table A-1 are based on the model vs. data categorization and the rows indicate the application according to system complexity beginning with Primitives (pipe, transistor), progressing through Assemblies (small ICs, control rods), and Components (Hard drive, motor, power supply), to Systems (cooling system, plant instrumentation). The goal of the research taxonomy is to align the three categories with the complexity of the equipment. In light of the discussions in section 4.1-.4.4 the reader will note that model-based applications will naturally dominate in simple systems while the data-driven applications will dominate in the more complex, higher-up in the system hierarchy, equipment. The research taxonomy validates this notion.

TABLE A-1 RESEARCH TAXONOMY.

Target Element	**No. of Examples and References**		
	Data-driven	**Hybrid**	**Model-Based**
Primitive (e.g. pipe, transistor)	**13** See Entries: D-1 - D-13	**3** See Entries: H-1 – H-3	**1** See Entries: M-1
Assembly (e.g. Small IC, control rod)	**7** See Entries: D-1-D-5; D-14-D-15 D-18	**4** See Entries: H-4 – H-7	**6** See Entries: M-2 – M-7
Component (e.g. Hard drive, motor, power supply)	**8** See Entries: D-1; D-14; D-16; D-17; D-19 – D-23	**5** See Entries: H-8 – H-12	**3** See Entries: M-8 – M-10
System (e.g. Cooling System, plant instrumentation)	**6** See Entries: D-14; D-20; D-24 – D-27	**1** See Entries: H-13	**0**

The bold faced numbers in each cell of the table indicate the number of references found, and the lower entries in each cell are the key to these references in the following subsection (e.g. H-4 is the 4th hybrid method). It is clearly seen that there are many more data-driven entries than model-based ones which is not too surprising since extensive physics of failure investigations are required to establish a model-based application. System level entries are predominantly in the data-driven column with none at all under model-based column. Failures at the system level can be due to many failure modes and it would be prohibitively expensive to develop a physics of failure model for each of them. Even the model-based entries at the component level are restricted to one or a few predominant failure modes. Discussions with active members of the scientific community[17] researching and developing the field of advanced

[17] In the development of this document, the authors held extensive interviews with leaders of this community from national laboratories (Idaho National Lab, Pacific North National Lab) NASA

prognostics indicate that the middle column of applications relying on the hybrid approach will most likely be the one most rapidly populated in the near future. The scarceness of sufficient data for effectively applying data-driven methods on the one-hand, and the intractability of physical models of complex equipment for applying model-based methods on the other, leads to this hybrid approach.

A.1.2 Review Taxonomy

The review taxonomy is aimed at reviewers of AD&P applications for specific equipment types. It is proposed as an alternative classification in which the row headings are the type of covered equipment and the columns are the Data/Hybrid/Model methods previously discussed. The goal of the review taxonomy is to align this classification with system type (mechanical, electromechanical and electronic). The discussion of the three categories did not highlight types of systems that are more likely to be monitored by data-driven or model-based applications. However, there is a correlation between these categories and the type of equipment and this correlation may be helpful for NRC staff when reviewing license applications: The review taxonomy will enable the reviewer to directly look up any other techniques for the same type of system, in any of the three categories. It will offer a knowledge base of what is in use and what is in development for this equipment under application
The review taxonomy presented in Table A-2 shows that to–date the preferred approach for mechanical elements is model-based and for electronic elements it is data-driven. This can be explained by the difference in the number of failure modes: one (or few) for mechanical elements and many for electronic elements. When there are more than a few failure modes the effort required to develop and verify detailed damage models becomes large. A few references appear in more than one column of Table A-2 because they are applicable to several element types.

Each of the cells in Table A-2 can be further expanded into the complexity categories used in Table A-1. Thus for the electronic hybrid cell the expansion into complexity categories is shown in Table A-3. This expansion capability is primarily mentioned as a possibility for future updates when a larger number of entries may have to be covered.

(Ames Prognostics Center of Excellence) and academia (University of Tennessee, Idaho State University). Discussions were also conducted with leaders of the industrial R&D and operations community through such organizations as IAEA, EPRI and INPO

TABLE A-2 REVIEW TAXONOMY

Element Type	Number of Examples and References		
	Data-driven	Hybrid	Model-based
Mechanical: Passive Piping, reactor vessels, coolant loops, core internals, fuel channels, rod housing	**0**	**0**	**2** See Entries M-1; M-6
Mechanical: Active Hydraulics, valves, steam/vacuum, control rod driving systems, rotating machines, diesel engines, bearings, cooling fans, turbines	**0**	**1** See Entries H-4	**5** See Entries M-2-M-4; M-6&7
Electro-mechanical Motors, sensors, actuators, generators, engines, machines, electric power systems	**2** See Entries D-21; D-23	**3** See Entries H-9 -H-12	**4** See Entries M-5; M-8-10
Electronic Primitives (resistors, capacitors, transistors, diodes), CMOS single dies, assemblies, memory, hard drives, cards (e.g. avionics, communication etc.), transformers, solder joints, cables, connectors, sensors	**26** See Entries D-1 - D-20; D-22 -D-27	**8** See Entries H-1-H-3; H-5 - H-8; H - 13	**0**

TABLE A-3 EXPANSION OF THE HYBRID ANALYSIS FOR ELECTRONICS

Complexity	References
Primitive	3 H-1 – H-3
Assembly	3 H-5 – H-7
Component	1 H-8
System	1 H-13

Perusal of this Appendix will show that several component types are entered multiple times. Prominent among these are bearings which have six explicit entries and several more in which they are covered as part of a higher element (generator, etc.). This is not too surprising since bearings are well known to be a source of failure. The entries differ in the type of sensor (temperature, vibration, acceleration, oil quality, and combinations of these) and in the algorithm used to compute RUL. Other multiple entry subjects include solder joints (ubiquitous in electronics and amenable to failure model construction) and hot carrier electrons (as a cause of degradation in electronics). All of these are potentially important for NPPs and NFCFs.

The taxonomy, in its two variants, highlights how the methodology categorization aligns with other system characteristics such as complexity and type. The categorization of data and model-based methodologies is accepted throughout the field of AD&P, although the exact terminology may vary. This categorization is indicative of the information one has on the system and dictates the tools one can use to derive diagnostic and prognostic evidence. However, students of this field and possible reviewers will most probably be exposed to AD&P techniques from the equipment side. The research taxonomy is useful for understanding how the methodologies can be used in real applications. The review taxonomy is useful for understanding how a particular application fits into the context of the entire field.

A.2 Applications: Annotated bibliography of taxonomy entries

The following sections provide descriptions of specific AD&P methods and technologies. The entries are labeled according to the taxonomy structure: D denoting data-driven (D-1 through D-27); H denoting hybrid (H-1 through H-13); and M denoting model-based (M-1 through M-10). The descriptions are intended to provide limited background on the application and technology; the equipment it can be used for; and the maturity of the technology and its usage. The entries are grouped under the titles introduced in Chapter 3.

A.2.1 Canaries

D-1: Fuses (Vichare & Pecht, 2006)

Target
Electronic assemblies and subassemblies

Technology
Fuse opening precedes/preempts assembly/component failure and indicates failure inducing conditions.

Implementation
Diagnostics: non-specific indication of an abnormal condition
Prognostics: none
Maturity: mature technology

D-2: Prognostic Canary CMOS Cells (Mishra, et al., 2002), (Ridgetop Group, 2012)

Target
CMOS single dies, small assemblies

Technology
Canary cells are sensitive to the same stressors as the prime equipment (voltage, current, temperature, humidity, radiation, vibration) and experience the same stress level but are programmed to fail earlier due to scaling which is achieved via increased voltage, current or both. Prognostic distance can be programmed to allow time to replace.

Failure modes and mechanisms
Electrostatics discharge (EDC), hot carriers, metal migration, dielectric breakdown, radiation effects.

Implementation
Diagnostics: none.
Prognostics: preempts failure and can provide estimate of RUL
Maturity: R&D and testing

D-3: Prognostic Canary solder joint Cells (Gu, 2009), (Gu, et al., 2007)

Target
Electronic primitives and assemblies, single dies

Technology
Canary cells are sensitive to the same stressors as the prime equipment (voltage, current, temperature, humidity, radiation, vibration) and experience the same stressor level.

Failure modes and mechanisms
Low cycle fatigue of solder joints

Implementation
Diagnostics: none.
Prognostics: preempts failure and can provide estimate of RUL
Maturity: prototype and commercial R&D

D-4: Prognostic Canary Corrosion Cells (Mishra, et al., 2002)

Target
Electronic primitives and assemblies

Technology
Canary cells are sensitive to the same corrosion stressors and experience the same stress level.
Impedance spectroscopy (phase and magnitude / frequency) are used to assess damage level.

Failure modes and mechanisms
Corrosion

Implementation
Diagnostics: none.
Prognostics: preempts failure and can provide estimate of RUL
Maturity: R&D

A.2.2 Performance Monitoring Techniques

D-5: Built In Current Sensors (BICS) (Smith & Campbell, 2000), (Pecuh, et al., 1999), (Xue & Walker, 2004)

Target
CMOS primitives and single die ICs, small assemblies

Technology
Supply current is monitored via BICS. Excess current used to identify faults

Failure modes and mechanisms
Bridging defects, open defects, parasitic defects

Implementation
Diagnostics: threshold and signatures
Prognostics: Trend and signatures
Maturity: R&D and test

D-6: MOSFET Performance Signatures (Kalgren, et al., 2007)

Target
MOSFET devices

Technology
Feature extraction from multiple performance measurements provides degradation signatures

Failure modes and mechanisms
Fractures and void spaces; gate-oxide breakdown; contact migration; semiconductors degradation (the failure mechanisms are thermal cycling, electromigration, hot carrier effects and time dependent dielectric breakdown)

Implementation
Diagnostics: thresholds and signatures
Prognostics: signatures and time trending
Maturity: Test and R&D stage

D-7: Marginal Checking: Cables and Connectors (Born & Boenning, 1989)

<u>Target</u>
Cables and connectors

<u>Technology</u>
Tracking of small changes to critical parameters:

- Impedance changes
- Physical damage

<u>Implementation</u>
Diagnostics: thresholds and signatures
Prognostics: signatures and time trending
Maturity: Test and R&D stage

D-8: Marginal Checking: Oscillators (Born & Boenning, 1989)

<u>Target</u>
Voltage controlled oscillators

<u>Technology</u>
Tracking of small changes to critical parameters:

- Output frequency
- Power loss
- Efficiency
- Phase distortion
- Noise

<u>Implementation</u>
Diagnostics: thresholds and signatures
Prognostics: signatures and time trending
Maturity: Test and R&D stage

D-9: Marginal Checking: FET (Vichare & Pecht, 2006)

<u>Target</u>
Field Effect Transistors

<u>Technology</u>
Tracking of small changes to critical parameters:

- Gate leakage current
- Drain source leakage current
- Drain source resistance

<u>Implementation</u>
Diagnostics: thresholds and signatures
Prognostics: signatures and time trending

Maturity: Test and R&D stage

D-10: Marginal Checking: Ceramic Chip Capacitors (Vichare & Pecht, 2006)

Target
Ceramic chip capacitors

Technology
Tracking of small changes to critical parameters:

- Leakage current
- Resistance
- Dissipation factor
- RF noise

Implementation
Diagnostics: thresholds and signatures
Prognostics: signatures and time trending
Maturity: Test and R&D stage

D-11: Marginal Checking: Diodes (Vichare & Pecht, 2006)

Target
General purpose diodes

Technology
Tracking of small changes to critical parameters:

- Reverse leakage current
- Forward voltage drop
- Thermal resistance
- Power dissipation
- RF noise

Implementation
Diagnostics: thresholds and signatures
Prognostics: signatures and time trending
Maturity: Test and R&D stage

D-12: Marginal Checking: Electrolytic capacitors (Vichare & Pecht, 2006)

Target
Electrolytic capacitors

Technology
Tracking of small changes to critical parameters:

- Leakage current/resistance
- Dissipation factor

- RF noise

Implementation
Diagnostics: thresholds and signatures
Prognostics: signatures and time trending
Maturity: Test and R&D stage

D-13: Marginal Checking: Amplifiers (Vichare & Pecht, 2006)

Target
RF power amplifiers

Technology
Tracking of small changes to critical parameters:

- Voltage Standing Wave Ratio (VSWR)
- Power dissipation
- Leakage current

Implementation
Diagnostics: thresholds and signatures
Prognostics: signatures and time trending
Maturity: Test and R&D stage

D-15: Load Cycle Counting (Vichare, et al., 2006), (Vichare, et al., 2007)

Target
Electronic assemblies

Technology
Load cycle counting is used to generate histograms for the distributions of load cycle features: cyclic range, cyclic mean load, rate of change of load, and dwell time. Diagnostic and prognostic models are based on these features

Implementation
Implemented with a solder joint damage model and compared with actual resistance.
Diagnostics: Thresholds are used for system level diagnostics
Prognostics: Based on damage model
Maturity: R&D

D-16: Marginal Checking: CMOS IC (Vichare & Pecht, 2006), (Born & Boenning, 1989)

Target
CMOS ICs

Technology
Tracking of small changes to critical parameters:

- Supply leakage current
- Supply current variation
- Operating signature
- Current noise
- Logic level variations

Implementation
Diagnostics: thresholds and signatures
Prognostics: signatures and time trending
Maturity: Test and R&D stage

D-18: Pulse Width Modulation (Khanniche & Mamat-Ibrahim, 2004)

Target
Voltage Source Inverters (VSI)

Technology
Monitoring of current pulse width modulation, and applying discrete wavelet transforms (DWT) and fuzzy logic used to identify faults.

Failure modes and mechanisms
Transistor open circuit faults and intermittent misfiring faults

Implementation
Diagnostics: applied to identify faulty devices in large integrated systems.
Maturity: R&D stage

D-19: Resistance Spectroscopy (Pradeep, et al., 2010), (Ridgetop Group, 2012)

Target
Ball grid Arrays (BGA); all connectors with multiple solder joints

Technology
Track resistance of edge connectors experiencing highest stress. Pre-failure signatures analyzed to estimate future state. Applicable to functional systems where corner interconnects in area-array packages are often redundant

Failure modes and mechanisms
Failures due to vibrations/mechanical stress.

Implementation
Suitable for prognostics.
Maturity: R&D as well as commercial tool.

D-20: Error Codes and Signals (Hecht, 2006)

Target
Digital memories and systems

Technology
The frequency of triggering error detecting codes for memories and communication increases as the devices age. Similarly the magnitude of the error signal in closed loop control systems increases in magnitude and changes in frequency spectrum as a function of damage processes to which the system is exposed. The rate of error triggers and the RMS magnitude of error signals furnish clues on component or system deterioration.

Failure modes and mechanisms
Threshold changes in semiconductors, gain reduction and mechanical degradation in closed loop systems

Implementation
Diagnostics: detection of error rates or error signal values exceeding baseline
Prognostics: time trending of excess error rates or error signal
Maturity: Test and R&D stage; see D-22 for use in disk memory errors

D-21: Pulse Width Modulation (Power Devices) (Zidani, et al., 2008)

Target
Motors: Voltage-Fed PWM Inverter Induction Motors

Technology
The proposed fuzzy technique requires the measurement of the output inverter currents to detect intermittent loss of firing pulses in the inverter power switches.

Failure modes and mechanisms
Misfiring (intermittent loss of firing pulses) in the switches of a PWMVSI induction motor drive

Implementation
Diagnostics: applied to identify faults in the inverter.
Maturity: R&D stage

D-22: Self-Monitoring Analysis and Reporting Technology (SMART) (ATA, 2008), (PCTechGuide, Undated), (PCGuide, 2001)

Target
Hard drives

Technology
Precursor monitoring via an interface between the computer startup program (BIOS) and hard disk drive. Measurements include variations on head flight height, error counts, variations in spinning time, temperature and data transfer rates among others.

Failure modes and mechanisms
Head damage: cracks, contamination, bad connections to electronics; motor/bearing: motor/bearing failure or wear; excessive run-out; no spin; electronic module failures: bad connections, chip failures; Media: scratches, defects, bad servo, ECC corrections

Implementation
Diagnostic: error values
Prognostic: trending of error values
Maturity: Mature technology for diagnostics

H-1: Performance Measurement (Circuit As a Sensor) (Nanduri, et al., 2007)

Target
CMOS RF devices

Technology
C-V and I-V characteristics of transistor change prior to actual breakdown and show up as signatures in device performance parameters such as gain, trans-conductance, series resistance and threshold voltage. These translate into analog circuit performance showing up in phase and frequency response, linearity, gain and impedance. Gate-source capacitance used for damage accumulation model.

Failure modes and mechanisms
Time Dependent Dielectric breakdown (TDDB) due to hot carriers

Implementation
Prognostics: Impact Technologies study in lab
Maturity: R&D and test

H-9: Model-based AD&P for Electro-Mechanical Actuators (Byington, et al., 2004), (Byington, et al., 2004)

Target

Electromechanical actuators (EMA), applicable also for other actuators: mechanical, hydraulic and electro-hydraulic,

Technology

Model simulates the actuator response to various command signals (e.g. flight control command signals); optimization algorithms estimate model parameters which are compared to the base (healthy) model. The residuals provide both diagnostic and prognostic information. (Parameters are physical such as friction-damping coefficient, local gear stiffness, torque constant, motor temperature)
As the technology is based on a simulated model of the performance of the actuator and its parts it can differentiate between different failure modes and provide information on the most advanced failure mode as well as the fastest progressing failure mode.

Failure modes and mechanisms:

Model-based prognostics can theoretically cover all failure modes (controller: electronic filter failure, loss of power, switch/connector failure, sensor failure; motor: bearing seizure, shaft misalign/fracture, windings open/short; gearbox: fatigue cracking, gear stripping; Acme configuration: cracked nut, cracked screw, nut seizes to screw; leadscrew/ballscrew: bearing seizure, jammed leadscrew). Failure modes implemented:

- Gear slipping
- Bearing seizure
- Motor failure

Implementation

Diagnostics & Prognostics: Implemented by Impact Technologies.
Maturity: commercial R&D & prototyping

H-10: Motor Current Signature Analysis (MCSA) / Motor Power Signature Analysis (MPSA) (IAEA, 2007) (IAEA, 2008), (Kryter & Haynes, 1989), (Strangas, et al., 2008)

Target

Electromechanical equipment: rotating machines driven by motors

Technology

Motor Current Signature Analysis (MCSA) / Motor Power Signature Analysis (MPSA) measure changes in mechanical loads which lead to changes in the current through the motor. Power analysis is sensitive to operational changes.

Failure modes and mechanisms

- Wear on: bearing, packing, coupling and gears
- Valve stem taper
- Stem nut wear

- Degraded voltage
- Degraded valve stem lubrication
- Worm gear tooth wear
- Obstruction in the valve seat area
- Motor pinion disengagement
- Degraded worm and work gear lubrication
- Changes in stem packing adjustment
- Improper torque switch settings

Implementation

Trending on monthly/quarterly basis offers qualitative prediction about machine deterioration.
Long term trending can diagnose improper operating conditions and improper maintenance (improper installation of seals packing gears bearings; inaccurate shaft alignment or rotor balancing). Provides an additional input to vibration analysis. It is simple to implement for online monitoring.
Maturity: In use

H-11: Electrical Signal Analysis of Electromechanical Generators (Kumar, et al., 2012)

Target

Electromechanical generators (wind power systems)

Technology

Analyze and trend electric output signals: frequency and phase.

Failure modes and mechanisms

- Wear on: bearing, packing, coupling and gears

Implementation

Trending can provide prognostic of the failing gear.
Maturity: R&D

H-13: Quality of Service. (Brown, et al., 2005), (Nanduri, et al., 2007)

Target

Communication equipment, possibly others

Technology

Estimating RUL based on combination of failure models and features based on quality of performance: GPS based on NMEA 0183 Protocol; Quadrature Amplitude Modulation (QAM) communication system CMOS failure models are the basis for accelerated fault-to-failure testing. Prognostics makes use of universal system level features: for GPS these are reported using the NMEA 0183 protocol, for the QAMCS these are based on Cyclic Redundancy Check (CRC). These require a simple RS232 connection between the communication device (GPS) and computer which analyzes the data.

Failure modes and mechanisms
Hot carriers lead to time dependent breakdown of dielectric and degradation of CMOS devices. This leads to system level functional failure (rather than operational)

Implementation
Implemented as experimental prognostic by Impact Technologies
Maturity: R&D and test

M-6: Physics Based Prognostics for Pneumatic Valves (Daigle & Goeble, 2011), (Daigle & Goebel, 2009)

Target
Pneumatic valves

Technology
Physical model applied to pneumatic valve. The physical parameters measured include opening degree, pressures, friction coefficient, response time. The model calculates an End of Life (EOL) probability distribution that can be translated to RUL

Implementation
Diagnostics: The measurements identify the damage and its location
Prognostics: Based on historical data a RUL is generated
Maturity: Currently implemented via simulation on historical (space shuttle) data. R&D stage.

M-8: Electrical Surge Analysis (IAEA, 2007)

Target
Motors: stator windings, (on both induction and synchronous machines), DC armatures, synchronous field poles

Technology Electrical surge comparison: Applying a transient surge at high frequency to two separate but equal parts of winding and comparison of the two, will indicate short circuit or open coil.

Failure modes and mechanisms
Turn-to-turn and phase-to-phase insulation deterioration; open circuit or reversal in connections in coils

Implementation
Trending can offer tracking of insulation deterioration and prediction on time to failure. Attempts to correlate conduction voltage to RUL are complicated by the differences in stresses on insulation during motor operation – the ability to operate with deteriorated insulation depends on load, start cycle frequency.
Trending can identify improper motor repair practices, as well as improper operating conditions (beyond design specifications).
Expensive – both instrumentation and requirement for highly trained/experienced operators.

Maturity: Electrical surge analysis is a mature quality control test method. The development of portable test instruments now allows this testing to be conducted on a troubleshooting and condition based maintenance basis.

A.2.3 Self-Test

D-14: Built-In Test: BIT (Pecht, et al., 2001) (Gao & Suryavanshi, 2002), (Drees & Young, 2004), (Motorola, 2002), (Johnson, 1996)

Target:

Large circuits, modules (avionics), systems (large scale systems, avionics, multi-chip, power supplies, remotely controlled systems). Logical devices: Cache, Bus, ASIC, ECC RAM, Serial EPROM, FLASH, NVRAM, Real time clocks;

Technology:

Built-in test (HW+SW): internal tests meant to detect hardware and software faults. These include: Error detection and correction circuits; totally self-checking circuits; self-verification circuits. Internal tests can include: register stuck-at conditions, register manipulations, device set-up instructions.
Roughly BIT are categorized as:

- Interruptive BIT (I-BIT) ;
- Continuous BIT (C-BIT) ;
- Periodic BIT (P-BIT).

Have relatively high false alarm rates that may be indicative of intermittent faults (Williams, et al., 1998), (Rosenthal & Wadell, 1990), (Allen, 2003)

Implementation

Diagnostics: Primary area of implementation
Prognostics: Not traditionally. Requires integration with stress models in order to evaluate precursors to failure
Maturity: Many mature applications for diagnostic purposes

D-22: Self-Monitoring Analysis and Reporting Technology (SMART) (ATA, 2008), (PCGuide, 2001) (PCTechGuide, Undated)

Target

Hard drives

Technology

Precursor monitoring via an interface between the computer startup program (BIOS) and hard disk drive: head flight height, error counts, variations in spinning time, temperature and data transfer rates.

<u>Failure modes and mechanisms</u>
Head damage: cracks, contamination, bad connections to electronics; motor/bearing: motor/bearing failure or wear; excessive run-out; no spin; electronic module failures: bad connections, chip failures; Media: scratches, defects, bad servo, ECC corrections

<u>Implementation</u>
Diagnostic: error values
Prognostic: trending of error values
Maturity: Mature technology for diagnostics

A.2.4 Multivariate Analysis

D-24: Support Vector Machines (SVM) Support Vector Classification (SVC) Support Vector Regression (SVR) (Sotiris & Pecht, 2007), (Cheng, et al., 2010)

<u>Target</u>
Electronic products, systems.

<u>Technology</u>
Applicable to multivariate analysis of large systems. Multiple sensors track surface insulation resistance (SIR), leakage current, cross talk, EMI, currents and voltages, vibration frequency, temperature, electrical resistance, inductance. SVMs used to classify and identify features. Data features are mainly statistical: mean, variance, distance measure, Eigen values. The analysis is sensitive both to improper functioning of single component or accumulation of small deviations of multiple components.

<u>Implementation</u>
Diagnostics: Thresholds are used to identify faults and determine severity
Prognostics: Time series provides progression of fault or damage and estimate prognostic distance
Maturity: R&D

D-25: Distance Metrics (Kumar, et al., 2008), (Kumar & Pecht, 2007)

<u>Target</u>
Electronic products, systems.

<u>Technology</u>
Applicable to multivariate analysis of large systems. Multiple sensors track surface insulation resistance (SIR), leakage current, cross talk, EMI, currents and voltages, vibration frequency, temperature, electrical resistance, inductance.
Distance metrics such as Mahalanobis Distance (MD) used to reduce multivariate data to univariate data.

<u>Implementation</u>
Diagnostics: Thresholds are used for system level diagnostics
Prognostics: Symbolic time series analysis uses MD for prognostics

Maturity: R&D

D-26: Projection Pursuit Analysis (Kumar, et al., 2008)

Target
Electronic products, systems.

Technology Applicable to multivariate analysis of large systems. Multiple sensors track surface insulation resistance (SIR), leakage current, cross talk, EMI, currents and voltages, vibration frequency, temperature, electrical resistance, inductance. The Projection Pursuit Analysis uses a Principal Components Analysis (PCA), least squares optimization (LS) and a Singular Value Decomposition (SVD) treatment of the data.

Implementation
Diagnostics: Thresholds are used for system level diagnostics. The Projection Pursuit analysis method was also used to identify 8 key parameters for root cause analysis of anomalies
Prognostics: very early research may lead to prognostic information as well
Maturity: R&D and test.

D-27: Continuous System Telemetry Harness (CSTH) (Gross, 2006), (Cassidy, et al., 2002)

Target
Computer systems (hardware + software)

Technology
Inputs include: system performance ("soft" variables: loads, throughput, queue length, bit errors), Physical variables (internal temperature, voltage, current, distributed), Canary variables (distributed synthetic transaction generators testing for user wait time 24/7). MSET (Multivariate State Estimation Technique) used to predict behavior of single variables. Sequential Probability Ratio Test (SPRT) used to detect deviations at particular time. Hundreds of sensors input to pattern recognition algorithms to identify faults. Redundancy managed through "inferential sensing" when sensors fail. Method also useful for diagnosing and healing/rejuvenating software (e.g. memory leaks, locks etc.)

Implementation
Diagnostics: thresholds and signatures
Prognostics: signatures and time trending
Developed by Sun Microsystems.
Maturity: Commercial R&D and prototype

M-10: Model Based Diagnostics of Electrical Power Systems (Mengshoel, et al., 2008)

Target
Electrical power systems

Technology
Sensors for each component (prioritized according to failure rates) provide input to a real time program. The models incorporate sensor failures via input from system commands.

Failure modes and mechanisms
Component and assembly failures: relays, batteries, inverters, sensors etc.

Implementation
Implementation requires agile algorithms that can be utilized in real time. Many implementations use Bayesian networks to diagnose failures based on sensor and command inputs. The application is mostly to diagnostic, rather than prognostic goals.
Maturity: R&D

A.2.5 Life Consumption Monitoring

H-2: Life Consumption Monitoring (Solder Joints) (Ramakrishnan & Pecht, 2003)

Target
Solder joints

Technology
Monitor stressors: temperature and vibrations. Estimate RUL based on damage/life consumption models.

Failure modes and mechanisms
Solder joint fatigue

Implementation
Prognostics: Temperature and vibrations monitored and damage model used to calculate "consumed life" and estimate RUL.
Maturity: R&D

H-8: Life Consumption Monitoring of modules/ TSMD (Harchani, et al., 2000), (Rouet & Foucher, 2004), (Shetty, et al., 2002)

Target
Modules (avionics), cards,

Technology
Monitor stressors: temperature and vibrations. Estimate RUL based on damage/life consumption models.
TSMD: Time Stress Measurement Device

Failure modes and mechanisms
Multiple failure modes: temperature and vibration induced failure modes.

Implementation
Prognostics: Temperature and vibrations monitored and damage model used to calculate "consumed life" and estimate RUL.
Maturity: R&D

M-1: Flow Accelerated Corrosion (Kim, et al., 2005), (Lee, et al., 2003)

Target
Piping

Technology
Online simulation of FAC condition (at elbows) using electrochemical and vibration sensors provides condition monitoring. Electrochemical sensors provide data on the amount of corrosive elements released into the flow. Vibration analysis provides direct measurement of local weight of the pipe wall

Failure modes and mechanisms
Wall thinning due to erosion and corrosion

Implementation
Diagnostic: provides information on location of thinning walls
Prognostic: provides information on remaining thickness
Maturity: implementation of integrated technologies is in R&D stages. Sensors exist and vibration based measurement of thickness exists.

M-4: Smart Oil Analysis (Byington & Schalcosky, Undated), (Byington, et al., Undated)

Target
Rotating machines, moving machinery, diesel engines

Technology
This technology uses smart oil sensors for measuring Electrochemical Impedance Spectroscopy (EIS) that provides over a wide range of frequencies information on both type and size of contaminants.

Failure Modes
Wear of metal components; breakdown of lubricants; external contaminants; failures of components that allow entry of moisture/water.

Implementation
Diagnostics and prognostics: allows diagnosing quality of oil. This can be used to assist in diagnosing structural damage or diagnose and provide prognosis on the breakdown of lubricants. The smart sensors allow for online implementation.
Maturity: Commercial R&D

M-6: Physics Based Prognostics for Pneumatic Valves (Daigle & Goeble, 2011), (Daigle & Goebel, 2009)

Target
Pneumatic valves

Technology
Physical model applied to pneumatic valve. The physical parameters measured include opening degree, pressures, friction coefficient, and response time. The model calculates an End of Life (EOL) probability distribution that can be translated to RUL

Implementation
Diagnostics: The measurement identifies the damage and its location
Prognostics: Based on historical data a RUL is generated
Maturity: Currently implemented via simulation on historical (space shuttle) data. R&D stage.

A.2.6 Vibration Analysis

H-4: Vibration Analysis of Rotating Elements (Harris, 2000), (Lacey, 2008), (Porotsky & Bluvband, 2012)

Target
Rotating elements in machines (bearings, cooling fans, turbans)

Technology
Use of diverse sensors: displacement, velocity and accelerometers, each provide coverage of different frequencies and amplitudes. Many different algorithms for feature selection and analysis. Time trending.

Failure modes and mechanisms

- Cracks, pits, and roughness in rolling element bearing components
- Unbalance of rotating machine parts.
- Shaft misalignment.
- Coupling problems.
- Bends, bows, and cracks in shafts.
- Excess sleeve bearing wear.
- Loose parts.
- Misaligned or damaged gear teeth.
- Deterioration caused by broken or missing parts.
- Deterioration caused by erosion and corrosion.
- Resonance of components.
- Electrical effects.

Implementation

Mature prognostics and diagnostics. Recent improvements provide more accurate RUL estimates. Implementation often in tandem with oil/fluid analysis.
Maturity: Mature technology

H-5: Vibration Analysis of Transformers (Wang, et al., 2010), (Rivera, et al., 2000), (Leibfield, 1988), (Hu, et al., 2012)

Target

Transformers, power transformers

Technology

Use of multiple accelerometers to analyze vibration of magnetic cores and windings

Failure modes and mechanisms

Structural failures of windings, supports and joints.

Implementation

As advanced diagnostic and prognostic tool still in R&D stage. Complements, temperature and oil analysis. Vibration analysis can be applied to prognostics
Maturity: technology in use

A.2.7 Acoustic Techniques

M-2: Acoustic Monitoring (IAEA, 2008), (IAEA, 2007),

Target

Hydraulic equipment; compressed air systems; steam systems; vacuum equipment; valves, fittings of valves, boiler tubes; feedwater heater tubes; reactor vessels and piping (heads, steam generator inlet/outlet pipes and fittings of closing holes); control rod housing; main stream lines; transformers; fossil high energy piping, primary coolant loop

Technology [18]

Monitoring of acoustic emissions and interpreting acoustic signatures characteristic of wear and deterioration:
Monitoring of acoustic emissions where none are expected signal changes in condition. For example:

- Motor operated valves that are nearly open or nearly closed will emit sound above background noise and indicate deterioration;
- Cavitation in pumps or pipes with high flow rates indicate a change that can result in rupture;
- Leaks are characterized by acoustic emission

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[18] Example of commercial tools: “Pulse Analyzer Platform” http://www.bksv.com/Products/PULSEAnalyzerPlatform/WhatisPULSE.aspx

Monitoring of changes in acoustic signatures of components with characteristic acoustic signals (e.g. engines) indicates condition changes.

Monitoring for transient emissions: Detect the transient sound of energy release with abrupt deterioration processes such as: crack development/propagation and material loosening and separating from wall. Pulses are analyzed and compared with test results or finite element models for diagnostic and prognostic information. Requires highly sensitive Piezo electric or strain gauge sensors

Acoustic monitoring is split into two ranges:
Sonic range – (0Hz – 20kHz) – The sonic range includes all frequencies in the hearing range of humans. Sonic range includes all frequencies used in mechanical vibration analysis and low frequency leak detection (2Hz – 20kHz)
Ultrasonic range – (20 kHz – 1MHz) - Ultrasonic frequencies are used in cavitation detection, acoustic emission, high frequency leak detection, corona and partial discharge detection.

Failure modes and mechanisms
Leaks, cracks, cavitation corona and partial discharge, interfacial bond failure; delamination of layers; transformer failures: degradation of insulation, inception of bobbles, localized heating in oil or paper, paper tracking or carbonization, hydrogen gas evolution, cavitation leading to nitrogen emission, oil pyrolysis, core winding, loose parts impinging on walls, irregularities.

Implementation
Diagnostics: Automatic recognition is mostly based on power spectra (using fast flux techniques) but also autoregressive analysis, wavelet decomposition , moment calculations, shifts of Eigen frequencies and higher harmonics. Shape and magnitude change are classified by expert systems. Improved algorithms distinguish events (e.g. loose parts impinging on walls) from background noise and allow for improved localization of events.
Prognostics: Trending of acoustic emission allows for tracking the progression of grain structure breakdown. Is being used for online continuous monitoring.
Sensors cannot withstand radiation and heat near reactor vessel – waveguides are used to attach the sensors, hence affecting the quality/sensitivity of measurement.
Maturity: Mature and very active technology. Commercial tools to interpret measurements and provide both diagnostics and prognostic information exist. New uses and more accurate implementation in R&D stages as well.

M-3 Ultra-Sound Test (Birks, et al., 1991), (Krautkrämer & Krautkrämer, 1990)

Target
Mainly applied to passive metal and alloy structures and components such as vessels, pipes. Can be used on concrete, wood and composites with differing resolution.

Technology
Ultrasound testing is performed with very short ultrasonic pulse-waves with frequencies ranging from 0.1-15 MHz and occasionally up to 50 MHz. These are directed into materials to characterize materials or detect internal flaws. A common example is ultrasonic thickness measurement, which tests the thickness of the test object, for example, to monitor pipe corrosion.
An ultrasound transducer connected to a diagnostic machine is passed over the object being inspected. The transducer is typically separated from the test object by a couplant (such as oil) or by water, as in immersion testing. (When ultrasonic testing is conducted with an Electromagnetic Acoustic Transducer (EMAT) the use of couplant is not required.) Literature acknowledges two modes of operation:

- Pulse-echo mode: in this mode the transducer both emits and receives the pulsed ultrasound wave as it is reflected by the boundaries in the material. These reflections indicate any defects or structures within a uniform substrate. In this mode only one surface must be accessible.
- Through-transmission mode: also called attenuation mode. A separate receiver measures the pulsed waves passing through the medium. The amount of attenuation indicates any changes in the uniformity of the medium.

Failure modes and mechanisms
Cracks, changes in thickness (due to corrosion or stress), shape changes

Implementation
Diagnostics: Not an automated tool but valuable due to the High sensitivity and high penetrating power, which allows for the detection of small flaws deep in the structure.
Maturity: Mature technology. Commercial tools in many industries requiring nondestructive methods, including aerospace, automotive and other transportation sectors, construction and medicine.

A.2.8 Targeted Micro/Macro-scopic Measurements

D-17: Molecular Test Equipment (MTE) (Wright & Kirkland, 2003), (Wright, et al., 2003), (Wright, et al., 2001)

Target
CMOS ICs

Technology
Molecular test equipment (MTE) within IC's: Carbon Nanotube technology is used to measure voltage, currents and chemical changes indicative of progression to failure

Implementation
Diagnostics: thresholds and signatures
Prognostics: signatures and time trending
Maturity: R&D stage

D-23: Signal Validation through Multi Level Flow Modeling (MLM) (Öhman, 2002), (Larsson, 2002)

Target
Sensors

Technology
Sensor signals validated by checking consistency between redundant sensors to detect flow leaks and sensor failures

Failure modes and mechanisms
Any sensor failures

Implementation
Diagnostic to detect failed sensors and false alarms
Maturity: R&D

H-3: Line Resistance Analysis (LIRA) (Fantoni & Toman, 2006), (Fantoni, 2009)

Target
Cables

Technology
Frequency domain analysis of high frequency resonance effects of unmatched transmission lines. Sensitive to small changes of wire electric parameters, mainly the insulation permittivity, that are a significant condition indicator of the cable state. Possibility to detect and localize small insulation cracks, in spite of different structures (insulation type, geometry) and non-aging related effects.

Failure modes and mechanisms
Thermal and radiation aging, humidity, insulation defects, mechanical damage.

Implementation
Diagnostics and prognostics.
Maturity: R&D and test

H-6: Dissolved Gas Analysis (IEEE, 2008), (IEC, 1999), (Golkhah, et al., 2011), (Mohd Radzian & Itoh, 2010), (Gavrilovs & Borscevskis, 2011)

Target
Transformers, power transformers

Technology
Analysis of gases (Methane (CH_4), Ethane (C_2H_6), Ethylene (C_2H_4), Acetylene (C_2H_2), Hydrogen (H_2), Carbon monoxide (CO), Carbon dioxide (CO_2), and non-fault gases are Nitrogen (N_2), and Oxygen

(O2).) dissolved in the insulating mineral oil. Pattern recognition (Neural Networks) applied to diagnose type of fault/degradation.

Failure modes and mechanisms

- Corona in oil ;
- Pyrolysis in oil;
- Arcing in oil;
- Pyrolysis in cellulose;

These faults lead to the degradation of the oil which will cause further damage

Implementation

Requires sample.

Diagnostic method only

Maturity: Technology in use

H-7: Circuit Voltage Analysis (Guo, et al., 2012)

Target

Small circuits including chips

Technology

Application of State Vector Machines to voltage measurements at several measuring points to identify characteristic patterns of several failure modes. Choice of measuring points is based on understanding failure modes, while the pattern recognition and diagnostics driven by data only.

Failure modes and mechanisms

- Circuit board damage
- Burned out chip
- Broken pins

Implementation

Diagnostics: identifies failures

Prognostics: None

Maturity: R&D

H-12: Tribology (Khonsari & Booser, 2008), (Bhushan, 2000), (Holmberg & Helle, 2008), (Glos & Sejkorova, 2012)

Target

Rotating machines, moving machinery, diesel engines

Technology
Tribology: size and composition of internal and external contaminants

- IR spectroscopy: nonmetal contaminants (from fuel, acids, degraded grease, additive deterioration);
- Particle counting;
- Total Acid Number (pH): oil oxidation/degradation;
- Viscosity: presence of fluid contaminants (water, fuel solvents) ;
- Water content;
- Spectrometric analysis: wear particles, contaminants, additive depletion;
- Ferrography: metal particles;
- Micropatch: large contaminants;

Failure modes and mechanisms
Wear of metal components; breakdown of lubricants, external contaminants, failures of components that allow entry of moisture/water.

Implementation
Mature diagnostic technology. Provides information on wear before vibrations can be detected. No other method to identify water in the lubricant, incorrect viscosity, oxidation and chemical breakdown. New "real-time sensors" are making online, automated, analysis possible for advanced diagnostics and prognostics. Progress made with mini-labs for onsite measurements: Mini-labs include: Wear debris analysis (WDA) (both quantitative: ferrous density, and qualitative: analytical); particle counting; water measurement: crackle or time resolved dielectric; oil chemistry: dielectric or voltametric or TAN/TBN; 40C viscosity.
Maturity: Mature technology

M-5: Coil Current Monitoring System (CCMS) (IAEA, 2007), (IAEA, 2008), (Westinghouse, Undated)

Target
Control Rod driving system (CRDS) control element driving mechanism control system (CEDMC)

Technology
Coil currents of Control Rod Driving System (CRDS) are monitored online at high sampling rate for timing sequence of CEDM motion, current amplitude and pattern mismatch of wave form.

Failure modes and mechanisms
Failures in coils, failures in Hall effect current sensors, failures in timing control cards, voltage adjustment cards and silicon controlled rectifiers (SCR)

Implementation
Diagnostics: Capable of fast diagnosis of condition of multiple elements in the CEDM and CEDMC (Control Element Driving Mechanism Control System).
Prognostics: Historic data can be trended to provide degradation trends and prognostics

Maturity: Newly commercial: Westinghouse has recently developed a commercial implementation.

M-7: Neutron Noise Surveillance and Monitoring (Including External) (IAEA, 2008), (Thie, 1981), (Park, et al., 2003), (CZIBÓK, et al., 2003), (IAEA, 2005), (IAEA, 2007), (Coble, et al., 2012) (Damiano & Kryter, 1990), (Fry, et al., 1984)

Target
Core internals, control rods, fuel channels, PHWR detector tubes

Technology
Neutron noise direct diagnostics: Process signal measured directly – to determine normal/abnormal function
Neutron noise spectral analysis (auto and cross spectra APSD, CPSD) or auto and cross correlation functions (ACF, CCF)

Failure modes and mechanisms

- Vibration: core, control rods, fuel channels (indicate structural wear but also generate wear)
- coolant boiling;
- moderator circulation;
- water level oscillations;
- Thermo-hydraulic instabilities;
- Propagating temperature fluctuations;
- BWR instabilities: void/pressure oscillations, Global, regional and local (due to unseating of a fuel assembly) instabilities.

Implementation
Noise due to vibrations, boiling, coolant flow, and temperature gradients are translated in the reactor core to neutron noise. Anomalies are identified as they are measured and compared to anomaly signatures (broadband, sink structure, peaks etc.).
To detect: one is required to know “signatures” of anomalies; to diagnose and localize origin of noise need to know the “core transfer function” either from measurements or model.
Implementation requires much planning as electronics and procedures are not part of original NPP design and there are many complex requirements:

- Multi-channel data acquisition systems for digitizing and storing detector signals;
- Multichannel optical isolation amplifiers separating data acquisition system s from station hardware;
- Maintenance procedures to connect and disconnect the systems without disrupting NPP operation;
- Digital data processing to operate offline on the recorded signals to produce multichannel statistical functions in the frequency and time domains for noise analysis;
- Physical models;
- Isolation requirements;

- Analog signal conditioning: signal is either analog current as direct output of sensor (self-powered flux detector, or flow transmitter), or analog voltage already transformed to standard voltage range;
- Measurement must be done at steady state high-power operation;
- Measurements for certain types of signatures (temperature signals) can require long times up to 12 hours.

Transient noise measurements can also be used (e.g. pump trip or startup, power step-back, pump changeover).

Core vibrations are diagnosed via spectral analysis of ex-core neutron detectors. Signals are processed via a fast Fourier transform to calculate the auto power spectral density (APSD), cross power spectral density (CPSD), coherence function and phase. Increasing amplitudes and decreasing frequencies indicate material degradation: loosening of the core barrel secondary support or wear of the hold-down springs. Both beam mode (pendulum) and shell mode vibrations are monitored. A mechanical model of the pressure vessel, core barrel and core barrel support (based on finite element model) greatly enhance the ability of the analysis to identify the mechanical problem through the structure Eigen modes.
Control rod vibrations detected via in-core neutron detectors (at least 3 required to identify the excessively vibrating rod) at different radial positions. Algorithms for identifying the rod are based on either parametric methods (localization curves) or empirical techniques (e.g. neural networks). In-core flux detectors detect the number of fuel channels vibrating based on coherence and phase measurements. Finite element vibration analysis is used to compare and identify abnormal vibration modes which indicate abnormal conditions of the end fitting support and the garter springs of the fuel channels.

Detector tube vibrations are detected by ICFDs via changes in flux due to non-homogeneous static flux field: Increase in vibration amplitude as well as impact with surrounding structures is detected via the ICFD noise analysis.

Neutron flux oscillations analyzed via local power range monitors (LPRM) and average power range monitors (APRM) indicate instabilities in BWR cores.
Measuring radial weighted average of in-core temperature noise accurately calculates the Moderator Temperature Coefficient (MTC) for diagnostics.

Maturity: Mature technology and application. Used extensively for testing in existing NPP. Automated/online implementation for diagnostics is more recent.

M-9: Resolver Channel Mismatch Detection (Brown, et al., 2008), (Kobayashi & Miya, 2004), (Clark, et al., 2001)

Target
Resolver position sensors

Technology
Analysis of voltage mismatch of the two output voltages is used to calculate the mismatch

Failure modes and mechanisms

Can only detect insulation faults occurring on the output windings (and not on the reference winding):

- Short circuits between windings
- Open circuits
- Short circuits to ground

Implementation

Diagnostic: Can be implemented in several ways: using additional hardware, or using only an algorithm applied to outputs based completely on model of mismatch. Provides diagnosis of size of mismatch.
Prognostic: Not implemented as prognostic. However, trending of mismatch size over time may be useful to generate RUL models. This may require a hybrid implementation.
Maturity: R&D.

Appendix B

B.1 Organizations, Centers and Communities

PHM Society: organizes an annual conference (the International Conference on Prognostics and Health Management) with proceedings, and publishes an online journal: The International Journal of Prognostics and Health Management (http://www.phmsociety.org/journal). The PHM society offers all publications free of cost and is a community conducive to the spreading of knowledge and results in the area of prognostic health management.

IEEE Reliability Society is one of the organizers of the Annual Reliability and Maintainability Symposium (see below) and is also the sponsor of IEEE Standards Project 1856, "(Draft) Standard for Prognostics and Health Management of Electronic Systems". The do tics: cument contains definitions of equipment levels, prognostic methodologies and procedures for their application. It is expected that this will facilitate propagation of PHM techniques that have been successful in one application to others.

The IEEE Systems Society holds an annual Conference on Prognostics and Health Management (PHM) and publishes the annual proceedings.

DOE Laboratories. The DOE National Laboratories, particularly PNNL and ORNL have dedicated staff working on diagnostics and prognostics and are the source of several publications referenced in this document.

The Prognostics and Health Management Consortium is a group established in the Center for Advanced Life Cycle Engineering (CALCE) at the University of Maryland. The group manages a collaborative research program leading to much progress in multiple domains of the prognostic engineering field.

Annual Reliability and Maintainability Symposium (RAMS) includes a prognostics track which offers an environment to exchange ideas and present academic results and commercial tools

IAEA: The IAEA has been active in sponsoring standards for prognostics

NASA: Of special interest are teams at NASA that are dedicated to research in the fields of nondestructive evaluation and testing as well as diagnostics and prognostics. The unique maintenance requirements of a space program (underlined by the difficulty or inability to perform maintenance in space) fuel a strong prognostics research program:

- Prognostics Center Excellence is located at Ames Research Lab and focuses on such systems as power supplies, batteries, sensors, wiring and electronics. The center has compiled a "Prognostics Data Repository" to ease the problem of availability of data that will allow the comparison and benchmarking of algorithm performance.

- NDEAA – The Non Destructive Evaluation and Advanced Actuators Technologies lab is located at JPL and advances research in this field.

B.2 Conferences

There are several other societies and publications whose proximity to the area of diagnostics and prognostics results in frequent presentations and publications in these areas. These include:

- The American Society for Nondestructive Testing: annual conferences and several publications;
- The Acoustical Society of America : holds annually the International Congress on Acoustics (ICA) and several publications;
- The Acoustical Society of Australia holds an annual meeting;
- IEEE: conferences in the area of diagnostics and prognostics are distributed among the IEEE societies: IEEE International Workshop on Defect Based Testing (DBT) (2000; 2004); IEEE Aerospace Conference; IEEE Transactions on Reliability; IEEE Instrumentation and Measurement Technology Conference Proceedings, 2008; IEEE Instrumentation Measurement Magazine;
- National conference on Innovative applications of artificial intelligence;
- International Conference on Artificial Neural Networks (ICANN);
- International Conference on Neural Information Processing (ICONIP);
- Association for the Advancement of Artificial Intelligence: Artificial Intelligence for Prognostics Fall Symposium (2007);
- The International Journal of Advanced Manufacturing Technology;
- International Journal of Nuclear Safety and Simulation.

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