DIRECTION DES ÉTUDES ET RECHERCHES
SERVICE ENSEMBLES DE PRODUCTION
DÉPARTEMENT RETOUR D'EXPÉRIENCES
MESURES-ESSAIS

EDF
Electricité de France

FR9703373

Août 1996

PROCACCIA H.
SILBERBERG S.

GUIDE DE GESTION DE LA SURETE DE FONCTIONNEMENT DANS L'INDUSTRIE ELECTRIQUE : DESCRIPTION DETAILLEE D'INDICATEURS DE SURETE DE FONCTIONNEMENT INTERNATIONAUX

GUIDELINE ON DEPENDABILITY MANAGEMENT FOR THE POWER INDUSTRY : DETAILED DESCRIPTION OF INTERNATIONAL POWERPLANT EQUIPMENT DEPENDABILITY INDICATORS

Pages : 48

97NB00001

Diffusion : J.-M. Lecœuvre
EDF-DER
Service IPN. Département PROVAL
1, avenue du Général-de-Gaulle
92141 Clamart Cedex

ISSN 1161-0611

VOL 28 № 22

SYNTHÈSE :

La Sûreté De Fonctionnement (S.D.F.) implique la gestion d'objectifs de fiabilité, disponibilité et maintenabilité. En 1993, une norme commune sur ces sujets a été publiée par l'IEC et l'ISO : IEC 300-1 : 1993 (Dependability Management - Part 1 : Dependability Programme Management), ISO 9000-4 : 1993 (Quality Management and Quality Assurance Standards - Part 4 : Guide to Dependability Programme Management).

L'UNIPEDE a créé un groupe d'experts (NUCLETHERMAINT), chargé d'établir un guide d'application de ces normes dans l'industrie électrique. Un premier guide d'application de procédures relatives à l'acquisition d'équipement, décrivant l'approche structurée d'un programme S.D.F. depuis les spécifications jusqu'à la mise en route d'un projet, a été publié en mai 1995. Le deuxième guide, concerne les indicateurs de S.D.F. des équipements, et est complémentaire aux indicateurs de performance des installations publiés par l'UNIPEDE. Il concerne les centrales fossiles et nucléaires. Cinq indicateurs de S.D.F. différents ont été identifiés afin de caractériser la maintenance effectuée sur les équipements et son impact au niveau du matériel, du système et de l'installation :

- I_1 : fréquence de maintenance associée à un matériel (nombre d'actions par matériel et par an),
- I_2 : effort de maintenance associé à un matériel (nombre cumulé d'homme-heures de maintenance par matériel et par an),
- I_3 : coefficient d'indisponibilité d'un matériel (%),
- I_4 : contribution d'un matériel à l'indisponibilité de la fonction d'un système (%),
- I_5 : contribution d'un matériel à l'indisponibilité de tranche (%).

Chacun de ces indicateurs peut être appliqué séparément pour évaluer les effets de la Maintenance Préventive, et ceux de la Maintenance Corrective, ce qui conduit à un total de dix indicateurs par matériel. Ces indicateurs permettent de caractériser la stratégie de maintenance et son efficacité sur les matériels clefs d'une installation, et constituent un outil de management au niveau de cette installation. Ce document propose en outre, une décomposition des centrales nucléaires et fossiles permettant de mettre en évidence les matériels qui présentent des effets dominants sur la S.D.F. de l'installation.

Il est recommandé d'utiliser ces indicateurs afin d'améliorer la fiabilité des équipements et par suite de réduire les coûts de fonctionnement grâce à une stratégie de maintenance et de stock de pièces détachées optimisé. Il est aussi recommandé d'utiliser ces indicateurs à des fins de comparaison internationale afin de mettre en évidence les dérives par rapport aux meilleures pratiques de maintenance entre compagnies d'électricité, et obtenir un maximum de bénéfices.

Ce document comprend cinq annexes : la première concerne le retour d'expérience des centrales PWR en France, au Japon et aux Etats-Unis, et montre l'interdépendance complexe qui peut exister entre les arrêts programmés et les arrêts fortuits des centrales. Les trois annexes suivantes, présentent des calculs d'indicateur de performance pour des matériels clefs : surchauffeurs primaires et pompes alimentaires. La dernière annexe, montre que relativement peu de matériels (une dizaine) sont responsables de la majorité des indisponibilités forcées (80 %), dans une famille de cinq centrales fossiles.

EXECUTIVE SUMMARY :

Dependability Managemnt involves the management of reliability, availability, maintainability and maintenance support, and in the power industry is necessary to ensure that plant meets the Reliability, Availability and Maintainability (RAM) targets set by the Utilities. In 1993, a joint Standard on Dependability Programme Management was developed by IEC and ISO : IEC 300-1 : 1993 (Dependability Management - Part 1 : Dependability Programme Managemen), ISO 9000-4 : 1993 (Quality Management and Quality Assurance Standards - Part 4 : Guide to Dependability Programme Management).

UNIPEDE established a group of experts (Nuclethermaint) to produce guidelines on its implementation specifically for use in the power industry. The present document comprises Part 2 of the guidelines and concerns equipment dependability indicators which complement the UNIPEDE plant performance indicators and can be applied to both nuclear and fossil plant. There are five different equipment dependability indicators, all relating to equipment maintenance activities and the impact that these activities have on the loss of both system function and unit capability, as follows :

- I_1 : equipment Maintenance Frequency (actions per item per year),
- I_2 : equipment Maintenance Effort (maintenance man-hours per item per year),
- I_3 : equipment Maintenance Downtime Factor (%),
- I_4 : equipment Maintenance Contribution to the System Function Downtime Factor (%),
- I_5 : equipment Maintenance Contribution to the Unit Capability Loss Factor (%).

Each of the above indicators can be applied separately to both preventive maintenance and corrective maintenance, giving rise to as many as ten indicator values for each item of equipment. Used in this way, the indicators provide a comprehensive picture of the maintenance strategy employed for key pieces of equipment, and its effectiveness. They are, therefore, a valuable managerial tool for improving maintenance activities at the unit level within a utility. This document provides guidance on the division of both nuclear and fossil power plant into their component parts and in each case the types of equipment having the most dominant effect on dependability are identified. These are the items which merit the greatest atention with regard to the equipment dependability indicators.

It is recommended that the equipment dependability indicators should be used within power stations to improve equipment dependability and, hence, reduce operating costs, particularly through the implementation of improved maintenance strategies and spare part policies. It is also recommended that the same indicators be used for the exchange of information for similar types of equipment between different utilities, and an illustration is given of the type of background information which must be included to ensure that such exchanges achieve maximum benefit. This can highlight where deviations from international best practice over the maintenance of critical plant items exist within a utility, thus identifying where the scope for improvement is greatest.

The document has five appendices. The first appendix uses historial data for PWR units in France, Japan and the USA to highlight the complex interdependencies that can exist between the durations of scheduled and forced outages. The next three provide examples of equipment dependability indicators calculated for key items of equipment, including primary superheaters and feedwater pumps, and include comparisons between different utilities as well as trends with time. The final appendix demonstrates that relatively few critical items of equipment (typically ten) have been responsible for over 80 % of the forced losses in any one year within a family of five fossil fired power stations.

CONTENTS

1. INTRODUCTION

Increasing commercial pressures are causing European Utilities to dispose of old, less efficient plant and, in some cases, to reduce levels of surplus generating capacity. This, in turn, is increasing the need for high availability from the newer operating units. The introduction of 'take or pay' fuel contracts is also increasing pressure on utilities to achieve high plant availabilities. At the same time it is necessary to reduce maintenance costs without an adverse effect on availability. Dependability measurement is necessary to ensure that the equipment will meet the RAM (Reliability, Availability and Maintainability) targets which must be attained. "Dependability" is the collective term used non-quantitatively to describe the availability performance and its influencing factors: reliability performance, maintainability performance and maintenance support performance (IEC 50 (191-02-03)).

To help utilities to meet these increased pressures, UNIPEDE has established a group of experts on the reliability, availability and maintenance of nuclear and thermal power stations (Nuclethermaint). One aim of this group is to produce guidelines on the implementation of Dependability Management in the power generation industry in accordance with the principles embodied in ISO 9000 - 4/IEC 300 - 1 "Dependability Management". Part 1 of these Guidelines, "Procurement of Equipment" was published in May 1995.

This document constitutes Part 2 of the Guidelines and describes five internationally agreed indicators of power plant equipment dependability, each of which can be used for corrective maintenance or for preventive maintenance, making ten indicators in all for each item of equipment. These dependability indicators provide a quantitative indication of plant equipment RAM performance and are intended to allow utilities to manage the performance of their own equipment and to identify where the need exists to adjust priorities and reallocate resources to achieve improved dependability. They may also be used to facilitate the exchange of operating experience information internationally for benchmarking purposes, and to identify performance trends with either calendar time or the service hours accumulated by the equipment.

While the indicators are primarily related to the operation and maintenance of power plant, they offer potential for wider application since:

- they provide valuable dependability characteristics to those responsible for the specification and procurement of equipment,

- they may be used to complement UNIPEDE's plant level performance indicators in the fields of operation, maintenance and design,

- using the maintenance-related indicators, it is possible to follow trends with time and to compare different designs and maintenance strategies.

The form of the indicators permits the exchange of data between utilities to assist with design decisions, availability predictions and operational assessment. The exchange of such data has already taken place during the course of the group's work on a trial basis, in order to identify any difficulties in applying definitions, system boundaries, etc.

2. BENEFITS OF MAINTENANCE AND FAILURE DATA GATHERING

At the time of writing these Guidelines, failure data gathering schemes are in routine use within many utilities, especially with regard to operational performance. In some utilities, however, maintenance data gathering schemes are a fairly recent development. Large international schemes also exist between utilities, as well as data exchange between utilities and suppliers. Examples of benefits achieved by UNIPEDE members are:

- optimization of the design of new plants,
- optimization of spare parts and of logistic resources policies for each individual unit,
- reduction of life cycle costs for each individual unit,
- maintenance optimization through RCM programmes[1] for each individual unit,
- data exchange and resulting modifications of existing plants,
- support of probabilistic safety assessments (mainly for nuclear plant),
- quantification of the value of redundant equipment,
- assessment of the value of R&D projects to improve plant Dependability,
- establishment of penalty-incentive schemes to improve Dependability,
- establishment of programmes aimed at protecting valuable plant from High Impact, Low Probability (HILP) failures.

Most of the data can be supplied on a cost effective basis by means of a practical data gathering scheme, keeping in mind:

- the purpose of the data,
- the amount of effort needed by utility personnel to supply consistent high quality data,
- feedback on the quality and use of the data to the parties involved.

As an example, optimization of the maintenance programme ideally requires the collection of the following:

- general plant, system, sub-system and component information,
- failure and maintenance history,
- modes, consequences and causes of failures,
- maintenance procedures,
- maintenance support and resources.

The most valuable dependability data are for items which have a significant effect on costs and data need only be analysed for the **dominant** equipment (see Section 5 and Appendix V). However, such data are generally scarce within any particular utility and if generating units continue to grow in size the amount will become even smaller. New units are continuously being improved and/or new equipment is used. While for totally new systems, one must still rely on engineering calculations, approximations and engineering judgement, for some sub-systems of a new system historical maintenance and failure data may be found that are applicable. Therefore, the exchange of data and data formats is desirable.

[1] RCM: Reliability Centred Maintenance.

In general, the exchange of dependability data between utilities from various countries, vendors, tenderers and different industrial sources will serve to identify and solve critical areas in the field of design, operation or maintenance of equipment. There should be no need to install equipment in new power plants that has been found to be troublesome in existing plants. Data exchange will facilitate the analysis of RAM as a function of time (trend analysis). Data exchange can also be used to verify RAM objectives or predictions.

Some worthwhile examples of analyses using maintenance data are given in the appendices:

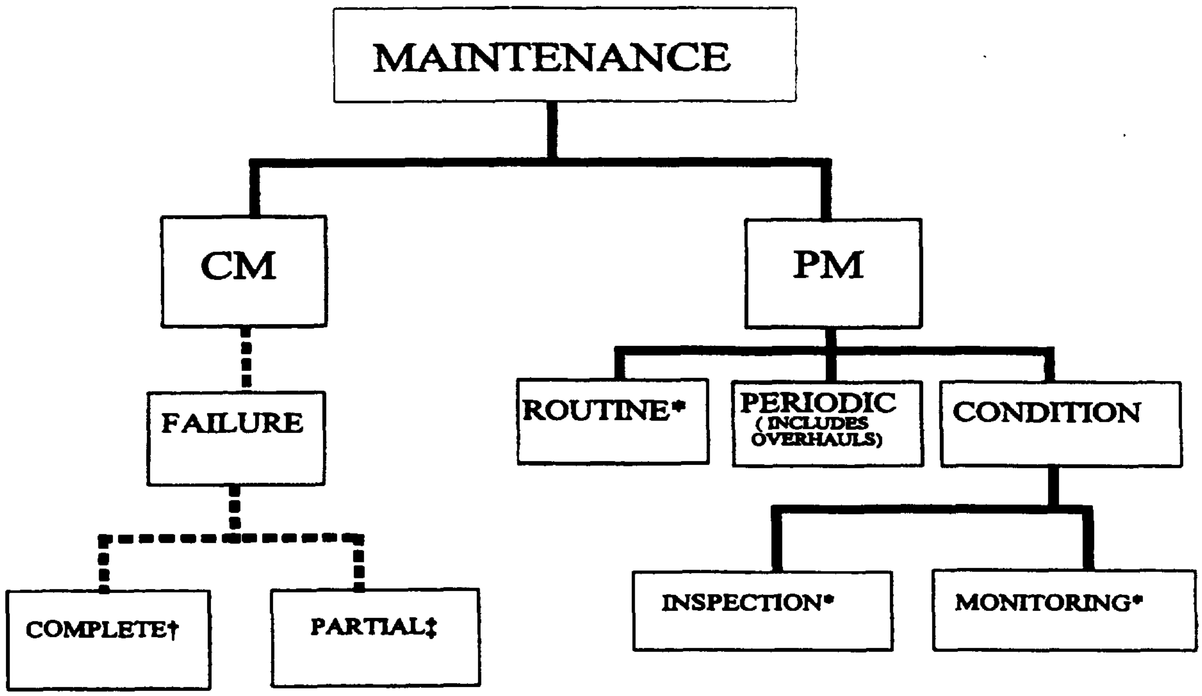
- Appendix I : Historic maintenance strategies for PWR units in France, Japan and USA,
- Appendix II : Calculation of equipment dependability indicators for corrective maintenance on the primary superheater of a 125 MWe oil-fired unit (19841992),
- Appendix III : Comparison of equipment dependability indicators for feedwater pumps,
- Appendix IV : Examples of trend analysis for corrective and preventive maintenance of twelve feedwater pumps,
- Appendix V : Influence of critical equipment on forced outages at five fossil-fired power stations (1992-94).
- Appendix VI : Maintenance performance indicators

3. GUIDANCE FOR CALCULATING THE INDICATORS

The dependability indicators provided in this document were developed to be as simple as possible, while still providing useful and meaningful trends and comparisons of equipment dependability within and between power plants. Each indicator relates to equipment belonging to a particular power plant type. Due to different possible failure modes, equipment belonging to nuclear power plants and fossil fired conventional plants (including gas turbine plants) have been dealt with separately to date. The dependability indicators could also be applied to other types of power plant such as hydro-electric and wind power installations. Based on additional experience with these indicators and the equipment proposed, revisions will be considered in the future.

3.1 Preventive Maintenance and Corrective Maintenance

The equipment dependability indicators are linked to maintenance activities and associated work (repair after a failure, preventive maintenance, inspection, tests, ...). Modifications, however much part of the process of improving plant Dependability, are not taken into consideration. This means that only preventive maintenance (PM) and corrective maintenance (CM) are involved (see Figure 1). **Therefore, the same indicators will be computed for these two maintenance types, PM and CM.**



† Complete failure denotes total loss of function
‡Partial failure denotes degraded performance

*** See Section 3.2**

Figure 1: Types of Maintenance

Corrective maintenance (CM) is carried out after recognition of a fault due to a failure which can be partial or complete (i.e. either some or all of the required functions cannot be performed). This approach derives from International Standard IEC 50 (191). Maintenance which is not corrective is termed preventive maintenance (PM). Component PM will only be taken into account in calculating dependability indicators if the availability of the equipment is affected by the preventive maintenance activity (see Section 3.2).

Maintenance actions relating to complete or partial failures which affect equipment availability and are judged to require immediate action should always be treated as corrective maintenance (CM). The criteria used to distinguish between CM and PM activities should be recorded when exchanging data between different utilities (see Table I). For example, where it is the case that maintenance activities are classified as PM whenever equipment can be kept running until the weekend following a failure, this should be stated.

All concurrent maintenance tasks performed on the same equipment should be regarded as either a single PM action or a single CM action.

PM can be carried out on an opportunity basis during CM and vice-versa. The rule is to be as simple as possible. So, to avoid double accounting, CM carried out during PM on the **same equipment** is considered as a single PM action; PM carried out during CM on the **same equipment** is considered as a single CM action. In other words, the type of maintenance recorded should relate to the activity with the longer duration, within whose shadow the other maintenance activity was conducted.

Preventive maintenance conducted during planned outages should be included in the calculation of the performance indicators. This could result in increased values of the indicators during years in which planned outages take place.

PM and CM are maintenance activities which are deeply connected. Each dependability indicator represents something which is significant by itself but the indicators as a group provide the means of dependability measurement. The information presented in Appendix 1 shows how relationships between the extents of planned outages (for PM) and forced outages (for CM) of PWR units in France, Japan and USA changed with time between 1980 and 1993. The development of an improved understanding of the causal relationships between preventive and corrective maintenance will clearly be of great value in connection with the development of improved maintenance strategies for plant.

3.2 Routine Maintenance, Inspection and Monitoring

Any action which does not cause equipment unavailability (as distinct from unit unavailability) is not taken into account when calculating the indicators and should be regarded as routine maintenance.

As examples, visual inspections, thermographic monitoring, and actions normally performed by shift operators (e.g. lubrication, ...) and considered as PM have no impact on dependability indicators (the equipment is not taken out of service).

3.3 Reference Time Period

The reference time period is the period during which the equipment is needed for its production or safety functions. The reference time period is usually taken to be one year (8760 h) since this facilitates the comparison of indicators from different sources. However, under exceptional circumstances, any other suitable period can be used as the reference time period provided that it is long enough to have significance and that the dependability indicators are normalized in terms of years.

3.4 Equipment Operational Mode

To facilitate the interpretation of dependability indicators, all equipment should be classified according to its mode of operation (baseload, peaking, etc.). The dependability indicators should apply to all these different possibilities and the operational mode will be determined by the time the equipment was in operation during the period of time under consideration.

The equipment operation factor, C_0, should be used to identify the equipment operational mode. This factor represents the ratio of the time that the equipment was in operation to the overall duration of the period of time under consideration:

$$C_o = \frac{t_o}{t_p}$$

where: t_o = total time the equipment was in operation during the overall period of time under consideration,

t_p = overall period of time under consideration, usually 1 year (8760 h).

To facilitate comparisons between different equipment with similar operational modes, it is useful to group values of the equipment operation factor into four different categories, as follows:

Baseload Category	(C_{01})	:	$C_o \geq 0.5$
Two-shifting Category	(C_{02})	:	$0.1 \leq C_o < 0.5$
Peaking Category	(C_{03})	:	$0.01 \leq C_o < 0.1$
Stand-by Category	(C_{04})	:	$C_o < 0.01$

3.5 Indicator Values at the Utility Level

RAM indicators can be calculated for a given item of equipment at both the unit level (i.e. for equipment from a single unit) and the utility level (i.e. for equipment from all similar units within a utility). For improved confidence in the results, dependability indicators should be calculated on as large a population as possible, and cover a period of several years. However, this population should be homogeneous, that is consisting of very similar types of equipment. It is bad practice to calculate average values for indicators based on components from different manufacturers or from different units that have encountered different modes of operation.

In order to limit the effects of outliers when determining an indicator value at the utility level from a distribution of individual values, the median value should be used rather than the average.

4. EQUIPMENT DEPENDABILITY INDICATORS

Five different Indicators are computed for both Preventive Maintenance and Corrective Maintenance. This means that for a given type of equipment 10 Equipment Dependability Indicators are provided in total.

The first Indicator (I_1) is related to maintenance frequency. The second Indicator (I_2) represents maintenance effort. The third one (I_3) concerns equipment unavailability. Both the fourth Indicator (I_4) and the fifth Indicator (I_5) are associated with the effects of equipment maintenance activities, at system function level and unit level, respectively: these effects, as for all indicators, depend on design, technical specifications and operation and maintenance conditions.

I_1 is linked to reliability performance and I_2 to maintainability performance and maintenance support performance. I_3, I_4 and I_5 are linked to availability performance.

When calculating the indicators I_4 and I_5 for preventive maintenance activities undertaken during planned outages, only that equipment whose preventive maintenance governs the duration of the planned outage (e.g. steam turbines or, on some occasions, gas turbines, electrical generators or boilers) should be taken into account. Double accounting must be avoided so work carried out in the shadow of other maintenance must make no contribution to the indicators I_4 and I_5.

Comment: Equipment downtimes depend on design, spare part holdings and personnel policies. The spare part holdings and personnel policies affect the equipment unavailability time but the equipment maintenance effort does not depend on waiting time for missing spare parts.

4.1 Equipment Maintenance Frequency (I_1)

4.1.1 Purpose

The purpose of this indicator is to monitor equipment reliability in terms of the corrective maintenance frequency and equipment maintenance policy in terms of the preventive maintenance frequency for each item of equipment.

4.1.2 Definition

The equipment maintenance frequency is defined as the number of maintenance actions per item of equipment (either corrective or preventive) per reference time period (expressed per year). As already stated, only maintenance actions undertaken while the equipment is unavailable due either to failure or for the maintenance procedure are to be taken into account.

4.1.3 Data Elements

The data required to determine the maintenance frequency for each item of equipment are the number of times the equipment has been under PM or CM activities during the reference time period.

4.1.4 Calculations

$$I_1 = \frac{\text{Number of Maintenance Actions per Item of Equipment}}{\text{Reference Time Period}}$$

The equipment maintenance frequency is determined by the cumulative number of maintenance actions per item of equipment during the reference time period (expressed per year): calculations are carried out separately for both preventive and corrective maintenance.

Corrective maintenance actions undertaken in response to unit trips and start-up failures should be taken into account when calculating I_1, even if they are of short duration.

4.1.5 *Worked Example (CM)*

The same equipment items will be used to illustrate the calculation of each of the five equipment dependability indicators for corrective maintenance (CM). Similar procedures can be used to calculate the indicators for preventive maintenance (PM). The selected equipment belongs to the cooling water (CW) system of a fossil-fired power station with two 350 MW units. This system is part of the common plant and includes two 50% capacity CW pumps (2 x 50%). Full output from each unit can be maintained when both CW pumps are running. Complete failure of both CW pumps results in the shutdown of both units due to complete loss of the cooling water system's functional capability, with 100% loss of output. The loss of either of the two 50% capacity pumps results in the loss of 50% of the cooling water system's functional capability. However, the loss of output from each unit when one pump fails is, on average, only 2%. This is due to decreased condenser efficiency resulting from the increase in cooling water temperature which occurs when only one CW pump is available. The station operates in baseload mode, with an equipment operation factor, C_0, for the CW pumps in the 1-year reference time period of 0.90.

During the year in question, there were three corrective maintenance events among the two CW pumps, as follows:

- pump seal failure on CW pump number 1,
- pump impeller failure on CW pump number 1,
- pump shaft failure on CW pump number 2.

Therefore:

$$I_1 = \frac{\text{Number of Maintenance Actions}}{\text{Number of Equipement Items} * \text{Number of Years}} = \frac{3}{2 * 1}$$

= 1.5 actions per item per year

4.2 Equipment Maintenance Effort (I_2)

4.2.1 *Purpose*

The purpose of this indicator is to identify the effort expended on maintenance activities at the equipment level. This indicator reflects the effectiveness of the equipment maintenance personnel in optimizing maintenance activities, as well as the magnitude of the task, and provides an overall indication of the effort with which key equipment is being maintained.

Note: this indicator does not represent the total cost of maintenance of the equipment, which obviously includes the cost of materials (spare parts, etc.) as well as labour. However, the comparison of equipment dependability indicators becomes too complicated when costs are included. Nevertheless, it is recommended that each utility records the material costs related to each maintenance event in order to review the policy over spare parts, etc.

4.2.2 Definition

The equipment maintenance effort is defined as the number of equipment maintenance man-hours (MMh), corrective or preventive, per item of equipment during the reference time period (expressed per year).

4.2.3 Data Elements

The data required to determine the maintenance effort for each item of equipment are the maintenance man-hours (MMh) spent on each maintenance action during the reference time period.

4.2.4 Calculations

The equipment maintenance effort is determined by the summation of MMh per item of equipment for the reference time period (expressed per year):

$$I_2 = \frac{\Sigma \text{ MMh per item of Equipment}}{\text{Reference Time Period}}$$

Note: MMh reflects the total effort needed for maintaining a given item of equipment and only that. In fact, it is not strictly equivalent to have three people working four hours or one person working twelve hours for the same result. The size and method of working of the maintenance team are also important. It is, therefore, useful to record the number of workers in the maintenance team and their shift pattern as well as MMh. MMh does not include the effort involved in manufacturing spare parts.

4.2.5 Worked Example (CM)

The equipment maintenance effort by a team of four fitters working single 8-hour shifts for each of the three corrective maintenance actions on the two CW pumps was as follows:

- seal replacement on CW pump number 1 12 MMh
- impeller replacement on CW pump number 1 96 MMh
- shaft replacement on CW pump number 2 *240 MMh*

Total 348 MMh

Therefore:

$$I_2 = \frac{\Sigma\,\text{MMh}}{\text{Number of Equipement Items} * \text{Number of Years}} = \frac{348}{2 * 1}$$

= 174 MMh per item per year

4.3 Equipment Maintenance Downtime Factor (I_3)

4.3.1 Purpose

The purpose of this indicator is to show the effects of equipment maintenance activities on equipment availability (e.g. downtime per boiler feed pump).

4.3.2 Definition

The equipment maintenance downtime factor is defined as the proportion of time a particular item of equipment is unavailable due to maintenance activities (corrective or preventive), expressed as a percentage of the reference time period.

The downtime is the duration, expressed in hours, that the equipment is unavailable because of preventive maintenance (PM) or corrective maintenance (CM). This means the time that the required equipment function cannot be fulfilled, even if the equipment is not required to operate at the time (i.e. the equipment is on stand-by).

4.3.3 Data Elements

The following data are required to determine the equipment maintenance downtime factor for each item of equipment:

- equipment maintenance downtime for PM or CM activities during the reference time period,
- the reference time period.

4.3.4 Calculations

The equipment maintenance downtime factor is determined as shown below:

$$I_3 = \frac{\text{Equipment Maintenance Downtime per Item of Equipment (hours)}}{\text{Reference Time Period (hours)}} * 100$$

where: Equipment Maintenance Downtime = cumulative durations of maintenance actions (including all delay times) during the reference time period.

Calculations are carried out separately for both preventive and corrective maintenance.

Comments: for PM, where maintenance is undertaken in the shadow of other maintenance during a planned outage, the normal scheduled equipment maintenance downtime should be used for calculating I_3.

For CM, the equipment maintenance downtime should commence when the failure is recognised.

4.3.5 Worked Example (CM)

The equipment maintenance downtime for each of the three corrective maintenance actions on the two CW pumps was as follows:

• seal replacement on CW pump number 1	24 h
• impeller replacement on CW pump number 1	75 h
• shaft replacement on CW pump number 2	*160 h*
Total	**256 h**

Therefore:

$$I_3 = \frac{\text{Equipment Maintenance Downtime (hours)}}{\text{Number of Equipement Items} * \text{Number of Years} * 8760 \text{ (hours)}} * 100$$

$$= \frac{256}{2 * 1 * 8760} * 100 = 1.46\%$$

4.4 Equipment Maintenance Contribution to the System Function Downtime Factor (I_4)

4.4.1 Purpose

Individual items of equipment are part of a system which has a function (or functions) to fulfil. Because of the maintenance activities and the consequent equipment unavailability, the system including the equipment may also become unavailable (e.g. where there is no redundancy of the particular item of equipment being maintained). The purpose of the function downtime factor is to measure the impact at the system level of equipment unavailability due to maintenance activities.

4.4.2 Definition

The equipment maintenance contribution to the system function downtime factor is defined as the system function downtime due to equipment maintenance (corrective or preventive) expressed as a percentage of the reference time period.

The system function downtime is the duration, expressed in hours, for which the system function is totally lost because of equipment downtime due to preventive maintenance (PM) or corrective maintenance (CM).

Note: the impact of equipment unavailability may be limited to the system functional level and there may be no effect at the unit level.

4.4.3 *Data Elements*

The following data are required for each item of equipment to determine the value of this indicator:

- system function downtime for PM or CM activities over the calendar year,
- the reference time period.

4.4.4 *Calculations*

For a given item of equipment, the equipment maintenance contribution to the system function downtime factor is determined as shown below:

$$I_4 = \frac{\text{System function Downtime per Item of Equipment (hours)}}{\text{Reference Time Period (hours)}} * 100$$

where: system Function Downtime = cumulative durations over which the system function is lost due to maintenance activities (CM or PM) during the reference period.

Calculations are carried out separately for both preventive and corrective maintenance.

Note: I_4 is time-based, not energy-based so deratings are not taken into account in computing I_4 (I_5, however, is energy-based).

4.4.5 *Worked Example (CM)*

The only complete loss of system function during the corrective maintenance of the CW pumps occurred when the impeller replacement on CW pump 1 overlapped the shaft replacement on CW pump 2 by 36 hours.

Therefore:

$$I_4 = \frac{\text{System Function Downtime (hours)}}{\text{Number of Equipement Items} * \text{Number of Years} * 8760 \text{ (hours)}} * 100$$

$$= \frac{36}{2 * 1 * 8760} * 100 = 0.2\%$$

4.5 Equipment Maintenance Contribution to the Unit Capability Loss Factor (I_5)

4.5.1 *Purpose*

The purpose of this indicator is to quantify the contribution of particular items of equipment to the unit capability loss. It is complementary to the unit capability loss factor, which is one of the unit performance indicators[2]. Its purpose is to identify which items of equipment contribute to unit capability loss due to either preventive maintenance or corrective maintenance (other factors contributing to unit capability loss, e.g. performance degradation due to climatic conditions, fouling, etc., are not included).

---

[2] see: Detailed Descriptions of International Power Plant Performance Indicators, UNIPEDE, June 1991.

4.5.2 Definition

The equipment maintenance contribution to the unit capability loss factor (I_5) is defined as the energy lost due to the unavailability of individual items of equipment because of corrective (or preventive) maintenance activities. It is expressed as a percentage of the energy that could have been produced by the unit operating at the Net Design Rating during the reference time period had maintenance not been taking place.

This definition is analogous to that given for the unit capability loss factor in the aforementioned document on power plant performance indicators but its scope is restricted to output losses directly related to the maintenance of equipment.

Reference energy generation is the energy that could have been produced if the unit had operated continuously at full power under reference ambient conditions throughout the reference time period.

Reference ambient conditions are the environmental conditions representative of the annual mean (or typical) ambient conditions that were assumed as basic design criteria for the unit.

4.5.3 Data Elements

The following data are required to determine the value of I_5 for each item of equipment:

- reference energy generation, expressed in megawatt-hours (electric), over the reference time period,
- unit energy loss due to preventive or corrective maintenance of a given item of equipment, expressed in megawatt-hours (electric), over the reference time period (only losses associated with maintenance activities, including delays due to shortages of spares and the unavailability of maintenance staff should be taken into account in calculating I_5)

4.5.4 Calculations

The equipment maintenance contribution to the unit capability loss factor is determined for each item of equipment subject to maintenance activities (preventive maintenance or corrective maintenance) during each reference time period, as shown below:

$$I_5 = \frac{\text{Unit Capability Loss per Item Equipment (MWh)}}{\text{Reference Energy Generation (MWh)}} * 100$$

where: reference Energy Generation is the energy that could be generated in the reference time period based on the Net Design Rating (MWh) and expressed in terms of the year (8760 hours).

and: equipment Maintenance Related Unit Capability Loss for the Item of Equipment corresponds to the equipment unavailability because of maintenance activities.

Calculations are carried out separately for both preventive and corrective maintenance.

- Unit Capability Loss for the Item of Equipment = energy losses over the reference time period. = Σ power loss x hours operated at reduced power (or shutdown) due to maintenance activity.

4.5.5 Worked Example (CM)

Maintenance on a single CW pump leads to a 2% loss of performance. For a 350 MW unit, this corresponds to a partial capability loss of 7 MW. Maintenance on both pumps together, leads to a complete capability loss of 350 MW.

The period of complete loss due to the CW pumps was only 36 hours (when the impeller replacement on pump number I and the shaft replacement on pump number 2 overlapped). Therefore, the capability losses associated with the three maintenance actions were as follows:

• seal replacement on CW pump number 1	24 h x 7 MW	=	168 MWh
• impeller replacement on CW pump number 1	36 h x 7 MW	=	252 MWh
• shaft replacement on CW pump number 2	124 h x 7 MW	=	808 MWh
• overlap of impeller and shaft repairs	36 h x 350 MW	=	*12600 MWh*
	Total		**13888 MWh**

$$I_5 = \frac{\text{Total Equipment Maintenance Related Unit Capability (MWh)}}{\text{Number of Equipement Items * Reference Energy Generation (MWh)}} * 100$$

$$= \frac{13888}{2 * 350 * 8760} * 100 = 0.23\%$$

4.6 Procedure for the Exchange of Data Between Utilities

To facilitate the exchange of meaningful data between utilities, when reporting values of the indicators, the number of items of equipment per unit should be stated, together with their capacities, so that it is clear what the level of redundancy of the equipment is in the unit under consideration. The size of the unit output (MWe) and its type (e.g. fossil-fired or nuclear) should also be recorded. Different types of equipment (e.g. turbine-driven and electric motordriven boiler feed pumps) should be treated separately. Table I shows typical information (in this case for the CW pump example) of the sort that should be included when exchanging data on indicators for a particular type of equipment between different utilities. This Table includes data relating to the earlier worked examples for CW pumps and is shown for illustrative purposes only. Any suitable format will suffice for the exchange of information on the performance indicators between different utilities, provided that sufficient background information is supplied to allow valid comparisons to be made. Either a similar or simplified format can be used for recording indicator values for management purposes within utilities.

Table 1 - Illustration of Information which should be reported when exchanging data between different utilities (based on earlier worked examples for CW pumps)

YEAR(S): 1995

Company: Fossil Power Company Limited

Unit Size: 350 MW **Fuel:** Coal

Number of Units: 2

Special Considerations: None
(e.g. Maintenance team size/work pattern)

Operating Mode	**Base load**	J
	Tow shift	O
	Peak load	O
	Stand-by	O

EQUIPMENT DETAILS

Type of equipment	Cooling Water Pump (Vertical Spindle Type)
Technical Characteristics	Flow = 14.6 m^3/s; Head = 16.5 m at full flow
Date of Manufacture	1972
Reference Time Period (hours)	8760
Operating Hours during Period	7884
System Configuration	2 x 50%
System Boundaries	CW screens/CW discharges valves
Total Number of Similar Items	2 (common to both units)

EQUIPMENT INDICATORS

C_o		0.90	**EXPLANATORY COMMENTS, IF ANY**
I_1	**CM**	1.5 a^{-1}	
	PM	12 a^{-1}	Monthly Plant Condition Monitoring (PCM)
I_2	**CM**	174 $MMha^{-1}$	
	PM	18 $MMha^{-1}$	Each monthly routine takes 3 MMh (2 pumps)
I_3	**CM**	1.46%	
	PM	0	PCM has no effect on availability
I_4	**CM**	0.20%	
	PM	0	PCM has no effect on system function
I_5	**CM**	0.23%	
	PM	0	PCM has no effect on unit capability

5. DIVISION OF PLANT INTO ITS COMPONENT PARTS

In principle, maintenance can be approached from a functional point of view at various levels within a power plant (Part, Component, System, Unit, Plant). However, experience has shown that the System level is the most efficient and functional level at which to undertake RAM analyses.

What is more, it has consistently been found that it is not cost-effective to apply RAM techniques to every System in the Plant because some of them have neither a history of failure nor excessive maintenance costs that might warrant a special investigation to improve them. It is important that the selection be done in a simple way without large expenditure of time and resources.

Generally the Systems that merit a RAM analysis can quickly be pinpointed from the ones with:

- high concern with respect to safety and environment,
- large numbers of CM actions in recent years or predicted for the future,
- frequent PM tasks/High PM costs,
- large contributions to full or partial outages.

As an example, for nuclear power plant, 30 to 40 systems may be chosen from over one hundred possibilities for the RAM analysis. These can be grouped into only 9 or 10 functional system groups, as shown in the following pages.

The situation for fossil power plant is less complex. Appendix 5 shows how only 10 or so systems were responsible for over 80% of the total losses of availability for the power plants concerned in any particular year.

5.1 Division of Nuclear Power Plant

The following division of nuclear power plant systems into functional system groups is consistent with that proposed by the IAEA[3] and the NPRDS[4] for light water reactors. The same principles can also be adopted for gas cooled reactors.

---

[3] Operating experience with Nuclear Power Stations in Member States, IAEA.

[4] Nuclear Plant Reliability Data System (NPRDS) Reporting Guidance Manual, The Institute of Nuclear Power Operations.

5.1.1 Functional System Groups

1. **Reactor Coolant Systems**

Includes: Reactor and accessories
Reactor cooling and steam generation system (including pressurizer (PWR) or main steam piping and isolation valves (BWR))
Steam generators.

2. **Operating Auxiliaries and Safety Systems**

Includes: Emergency Core Cooling Systems
Containment protection and surveillance
Coolant volume, purification, chemical, sampling
Residual Heat Removal System
Emergency Feedwater System
Component Cooling Water System

3. **Reactor Instrumentation and Control Systems**

Includes: Control rods and drives
Neutron monitoring
Reactor instrumentation
Reactor control and protection logic

4. **Turbine Cycle Systems**

Includes: Turbine, control valves and stop valves
Moisture separators and reheaters
Turbine control system

5. **Feedwater and Steam Systems**

Includes: Condensers, condensate treatment system
Feedwater heaters
Feedwater pumps and piping
Steam piping (including Main Steam Isolation Valves (PWR))
Steam generator blow-down

6. **Generator and Electrical Systems**

Includes: Main generator
Electrical power supply systems, main transformers, emergency diesel generators, ...

7. **Radwaste Treatment Systems**

Includes: Gaseous, liquid and solid radwaste treatment

8. **Containment System**

   Includes: Penetrations

9. **Other Systems**

   Includes: Circulating water systems
   Fire protection systems, ventilation and conditioning systems
   Fuel handling and storage
   Miscellaneous systems

5.1.2 Equipment Types

1. **Accumulators, Tanks, Vessels and Pipes**

   Includes: Low pressure tanks and high pressure devices

2. **Electrical Equipment**

   Includes: Generators
   Transformers
   Electrical motors
   Electrical heaters

3. **Heat Exchangers**

   Includes: Steam generators
   Condensers
   Evaporators
   Coolers

4. **Instrumentation and Control**

5. **Engines (e.g. diesel motors)**

6. **Turbines**

7. **Pumps and Fans**

8. **Valves**

9. **Others**

5.1.3 The Reference Matrix For Nuclear Power Plant

Each item of equipment can be placed on the matrix shown below:

System Groups Equipment Types	1 Reactor coolant systems	2 Operating auxiliaries and safety systems	3 Reactor I & C Systems	4 Turbine cycle systems	5 Feedwater & steam systems	6 Generator & electrical systems	7 Radwaste treatment systems	8 Containment	9 Other systems
1. Accum. pipes vessels									
2. Electrical									
3. Heat exchanger									
4. I & C									
5. Engines									
6. Turbines									
7. Pumps and fans									
8. Valves									
9. Others									

5.1.4 The Equipment to be Monitored

The list of equipment to be monitored can change because of changes of interest and technology.

As an example, Section 5.1.5 overleaf shows the reference matrix for a PWR with the following list of equipment inserted. In this list, the first digit relates to the System Group (based on IAEA proposals) while the second relates to the Equipment Type (based on NPRDS recommendations).

1.1 Pressurizer (PZR)
1.3 Steam generators (SG)
1.7 Primary pumps (RCP)
1.8 Relief and safety valves

2.7 Control and Volumetric Control System (CVCS) pumps

3.4 Control rods & Control rod drive mechanism (CRDM)
In-core instrumentation

4.3 Moisture separator and reheater (MSR)
4.6 Main turbine
4.8 Control & stop valves

5.3 Condensers
5.6 Main feedwater pump turbines
5.7 Main feedwater pumps (MFP)
5.8 Main feedwater regulating valves (MFW reg. valves)
Main steam isolation valves (MSIV)

6.2 Main generator (MG)
6.5 Emergency diesel generators (EDG)

9.9 Refuelling machines

5.1.5 Example of a Completed Matrix for a Nuclear Power Plant

System Groups / Equipment Types	1 Reactor coolant systems	2 Operating auxiliaries and safety systems	3 Reactor I & C Systems	4 Turbine cycle systems	5 Feedwater & steam systems	6 Generator & electrical systems	7 Radwaste treatment systems	8 Containment	9 Other systems
1. Accum. pipes vessels	PZR								
2. Electrical					MFP motor	MG			
3. Heat exchanger	SG			MSR	Condenser				
4. I & C			CRDM, In-core inst.						
5. Engines						EDG			
6. Turbines				Main turbine	MFP turbine				
7. Pumps and fans	RCP	CVCS Pump			MFP				
8. Valves	Relief & Safety valves			Control & stop valves	MFW Reg. valves MSIV				
9. Others									Refueilling machines

5.2 Division of Fossil Fired Conventional Power Plant

The equipment in a fossil fired power plant can be categorised in two ways: in terms of Functional Group or Equipment Type. Examples of these two types of division are given below. These include gas turbines, which may be used in simple cycle mode (e.g. to provide a black start capability) or in combined cycle mode.

5.2.1 Functional System Group

1. **Boiler**

   Includes: Pipes, vessels, ...
   Heat exchangers
   Instrumentation and Control
   Valves
   Firing equipment
   Environmental

2. **Boiler Auxiliaries**

   Includes: Electrical
   Heat exchangers
   Pumps, Fans and Other rotating equipment
   Valves
   Fuel handling
   Environmental

3. **Turbine Systems**

   Includes: Instrumentation and Control
   Turbines
   Pumps, Fans & Other rotating equipment
   Valves and Others

4. **Feedwater and Steam Systems**

   Includes: Pipes, vessels, ...
   Electrical
   Heat exchangers
   Instrumentation and Control
   Turbines
   Pumps, Fans & Other rotating equipment
   Valves

5. **Generators and Electrical Systems**

   Includes: Electrical
   Instrumentation and Control
   Generator rotor and end bells

6. **Block Auxiliary Systems**

Includes: Pipes, vessels, ...
Electrical
Engines
Pumps, Fans & Other rotating equipment
Valves
Other equipment
Fuel Handling

7. **Gas Turbines**

Includes: Pipes, vessels, ...
Electrical
Heat Exchangers
Instrumentation and Control
Turbines
Pumps, Fans & Other rotating equipment
Valves
Other equipment
Firing equipment
Fuel Handling
Environmental

5.2.2 Equipment Types

The division presented below gives the second categorisation of plant:

1. **Accumulators, Pipes, Vessels, etc.**

Includes: Steam drum
Feedwater storage tank
Cooling water filters and piping

2. **Electrical**

Includes: Electrical motors (Forced draft, Induced draft, Primary and Secondary Air and Gas recirculating fans)
Electrical motors: Feedwater and condensate pumps
Electrical motors: Cooling water pumps & air compressors
Generator: Windings, magnetic circuit & excitation
Breakers and Transformers
Rectifiers, converters & batteries (aux. voltage)
Switchboards and Transformers

3. **Heat Exchangers**

Includes: Water wall tubes
Superheater
Reheater
Economizer
Regenerative air heaters
HP & LP feed heaters
Condensers

4. **Instrumentation and Control**

Includes: Drum level control
Burner control
Boiler protection/control
Turbine regulation/control & protection
Generator protection
Feedwater accumulator/condenser control
Feed heater control
Excitation control
Digital control system (DCS)

5. **Engines**

Includes: Diesel engine
Fire engine

6. **Turbines**

Includes: Main turbine: HP, IP & LP turbines
Turbine driven feedwater pumps
Gas turbines

7. **Pumps, Fans & Other Rotating Equipment**

Includes: Feedwater & condensate pumps
Generator rotor & end bells
Cooling water pumps
Cooling water tower and pumps
Forced draft & Primary air fans

8. **Valves**

Includes: Relief & safety valves (boiler)
Main steam and water valves
Turbine bypass valves
Control, stop & non-return valves (turbine)
Feedwater and condensate valves

9. **Other Equipment**

Includes: Sootblower system (Boiler auxiliary system)
Water and Waste Treatment Plant (Block auxiliary system)
Electro-chlorination (Block auxiliary system)

10. **Firing Equipment**

Includes: Burners
Combustors
Refractories
Front end equipment

11. **Fuel Handling**

Includes: Coal mills and Feeders
Fuel oil heating
Bunkers, Stackers and Reclaimers
Conveyors
Natural gas handling equipment

12. **Environmental**

Includes: Bottom ash system & Drag link
Flue gas desulfurisation
Scrubbers
Electrostatic precipitators
DENOX equipment

5.3 The Equipment to be Monitored

Maintenance Indicators need only be applied to those items of equipment (≈ 20%) that make the main contribution (≈ 80%) to the unavailability and/or to the maintenance costs in the power plant. As an example, the next page shows the Reference Matrix. On the basis of historical information and group members' experience, certain equipment types dominate unavailability and/or maintenance costs. These types of equipment are given in the matrix.

Since only a limited amount of experience exists with coal gasification plants in combination with gas turbines, critical items for this type of plant have not been included in the matrix.

5.3.1 The Reference Matrix For Fossil Power Plant - Each item of equipment can be placed on the matrix as shown:

System Groups / Equipment Types	1 Boiler	2 Boiler auxiliaries	3 Turbine systems	4 Feedwater & steam syst.	5 Generator & electrical syst.	6 Block aux. systems	7 Gas turbine
1. Pipes, vessels,...	Steam drum & headers			Feedwater storage tank		Cooling water filters & piping	Ducting to HRSGs
2. Electrical				Electrical motor Main feedwater pumps	Generator & exceitation Main transformer	Electrical motor Cooling water pumps	
3. Heat exchangers	Water wall tubes Economizer Superheater & Reh'r	Regenerative air heater Distric heating coils		Condensers HP & LP feed heaters			
4. Instrum. & control	Drum Level Control		Turbine regulation/control & protection	Feedwater Control			Burner & temperature control
5. Engine							
6. Turbines			Main turbines (HP, IP & LP)	Auxiliary turbines			Turbines (first row discs and blades)
7. Pumps, fans & other rot. equip.		Forced Draft and Induced Draft Fans		Main feedwater pumps Condensate pumps	Generator rotor & end rings	Cooling water pumps	
8. Valves	Relied and Safety Valves	Main Steam & Water Valves	Control, stop & non-return valves				
9. Other quipment							
10. Firing equipment	Refractories Burners						Burners & Transition Pieces
11. Fuel Handling		Coal mills & feeders Fuel oil preparation				Bunkers, conveyors & Stackers-reclaimers	
12. Environmental	Electrostatic Precipitators	Bottom ash system & Drag Ling				SO_2 scrubbers	

6. EQUIPMENT BOUNDARIES

For many reasons, it is difficult to agree the most appropriate equipment boundaries: design, operation and maintenance personnel, etc. have different view points; dependability indicators take into account different concepts which concern equipment through its function, its use and its maintenance.

Systems, by definition, usually have one or two top level functions and a series of supporting functions that constitute a logical grouping of equipment.

Considerable flexibility is allowed in defining precise boundary points to allow equipment to be grouped in the most efficient manner for analysis purposes.

However, to maintain consistency between different data sources, some general agreement on equipment boundaries for apportioning the maintenance actions is appropriate.

Whatever decisions are reached on boundary definitions, they must be clearly stated and documented as a part of the analysis process.

Bearing in mind the benefits of keeping things as simple as possible, a component should be divided into several sub-components and, of course, any part belonging to the component should be allocated to only one sub-component. The matrices proposed in Section 5 enable the data for each sub-component to be recorded and the use of these matrices should facilitate the acquisition of data for a given component.

As an example, the component CVCS "Pump" should be divided into two subcomponents, the "Motor" and the "Pump" itself. The "Motor" includes: rotor, stator, lubrication, cooling, and internal instrumentation. The "Pump" includes: the pump itself, the gearbox, lubrication, and internal instrumentation[5].

---

[5] see EIREDA, Vol. 2, Second Edition, 1995.

7. CONCLUSIONS AND RECOMMENDATIONS

Plant equipment dependability indicators provide a quantitative indication of equipment RAM performance. Detailed descriptions of five such indicators have been agreed internationally by UNIPEDE's group of experts on the reliability, availability and maintenance of nuclear and thermal power stations (Nuclethermaint). Each of these indicators can be applied separately to those corrective **and** preventive maintenance activities related to equipment unavailability, giving rise to a total of up to ten indicators for each piece of equipment. Used in this way, the indicators can provide a comprehensive picture of the maintenance strategy employed for key pieces of equipment, and its effectiveness.

Guidance is also given on the division of both nuclear and fossil power plants into appropriate systems and equipment types for evaluation. This facilitates the identification of the equipment which is most important with regard to dependability.

The five indicators of equipment dependability are as follows: (appendix 6)

- equipment Maintenance Frequency (I_1),
- equipment Maintenance Effort (I_2),
- equipment Maintenance Downtime Factor (I_3),
- equipment Maintenance Contribution to the System Function Downtime Factor (I_4);
- equipment Maintenance Contribution to the Unit Capability Loss Factor (I_5).

The first indicator, I_1, reflects equipment reliability performance, while I_2 is an indicator of equipment maintainability and of the performance of the maintenance support function. The remaining indicators, I_3, I_4 and I_5, are all linked with various aspects of availability at the equipment, system function and unit levels, respectively. These indicators complement, at the equipment level, the ten plant-level performance indicators that were developed by UNIPEDE in 1991.

It is recommended that these indicators should be used within power stations to improve management of equipment dependability. In particular, this can be of value in optimising maintenance strategies and improving spare part policies and the design of new plant.

Provided that attention is paid to specifying equipment boundaries precisely, and to recording the size, type, level of redundancy, and mode of operation of the particular equipment under consideration, together with the size and work pattern of the maintenance team, it is further recommended that the same indicators be used for the exchange of information for similar power plants within and between different utilities. The group's experience has shown that this can be of great value as a means of benchmarking dependability performance for key items of equipment and of identifying where there is scope for improvement through the implementation of company (or international) best practice.

APPENDIX I: HISTORIC MAINTENANCE STRATEGIES FOR PWR UNITS IN FRANCE, JAPAN AND USA (IAEA DATA)

Figure AI1 below shows historic information on the duration of forced and scheduled outages for PWR units in France, Japan and the USA between 1980 and 1993. This highlights the interdependence of scheduled outages (for PM) and forced outages (for CM). An improved understanding of the factors governing such relationships would facilitate the development of optimised maintenance strategies.

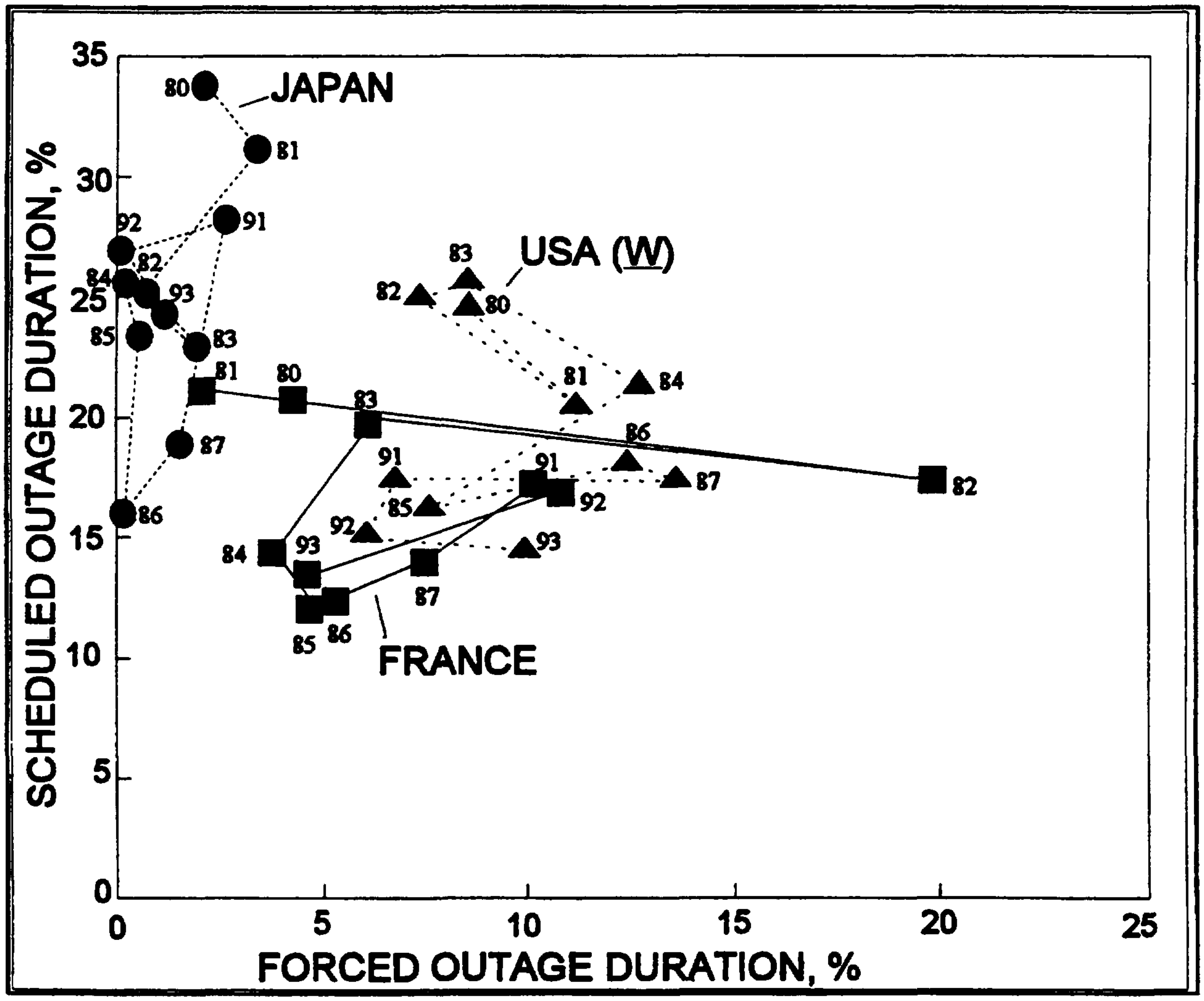


Figure AI.1 Trends in relationships between the durations of scheduled and forced outages for PWR units in France, Japan and the USA (1980-93)

Details of the number of units on which each of the above data points was based are given in the Table AI.1 overleaf, as is an additional Figure showing the cumulative results. These suggest that the emphasis placed on planned maintenance in Japan is associated with a low incidence of forced outages relative to those in France and the USA.

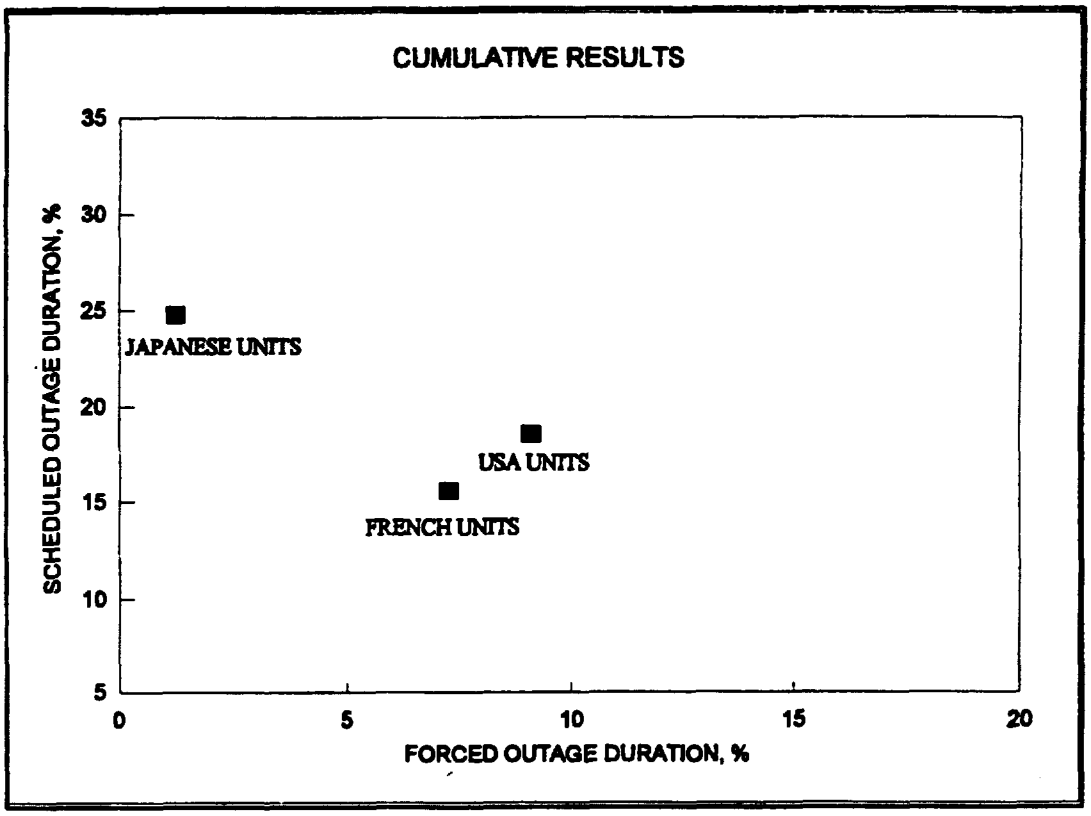


Figure AI.2 Comparison of cumulative relationships between scheduled and forced outages of PWR units in France, Japan and the USA

Table AI.1 - Summary of input data used in Figures AI.1 and AI.2

Year	**Number of PWR Units**		
	France	**Japan**	**USA (W)**
1980	6	8	24
1981	14.5	8.8	25
1982	19	9.8	29
1983	21.2	10	30
1984	24	10.5	31
1985	28	12.5	33
1986	34	12	37
1987	38	12	39
1991	49	15	51
1992	51	18	50
1993	53	18.8	50

APPENDIX II: CALCULATION OF EQUIPMENT DEPENDABILITY INDICATORS FOR CORRECTIVE MAINTENANCE ON THE PRIMARY SUPERHEATER OF A 125 MWe OIL-FIRED UNIT (1984-1992)

The unit under consideration began industrial service in May 1969 but statistical data are only available from 1984 onward. The following table summarises the data for the calculation of the indicators:

Year	Operation Time (h)	Unavailable Time (h)	Reference Time Period (h)	Failures (number)	Maintenance Man-hours for repair (Mmh)
1984	4011	104	8760	1	400
1985	4011	266	8760	4	952
1986	5270	46	8760	1	136
1987	1597	0	8760	0	0
1988	949	0	8760	0	0
1989	7412	0	8760	0	0
1990	5522	148	8760	1	576
1991	5757	0	8760	0	0
1992	6750	0	8760	0	0
1984-92	**41279**	**564**	**78840**	**7**	**2064**

The calculated numerical values for the equipment dependability indicators are:

Year	Indicators					Factor
	I_1 (a^{-1})	I_2 ($MMha^{-1}$)	I_3 (%)	I_4 (%)	I_5 (%)	C_o
1984	1	400	1.19	1.19	1.19	0.458
1985	4	952	3.04	3.04	3.04	0.458
1986	1	136	0.53	0.53	0.53	0.602
1987	0	0	0.00	0.00	0.00	0.182
1988	0	0	0.00	0.00	0.00	0.108
1989	0	0	0.00	0.00	0.00	0.846
1990	1	576	1.69	1.69	1.69	0.630
1991	0	0	0.00	0.00	0.00	0.657
1992	0	0	0.00	0.00	0.00	0.771
1984-92	**0.77**	**229.33**	**0.72**	**0.72**	**0.72**	**0.524**

Note that because the superheater has no redundancy and there is no possibility of derating, $I_3 = I_4 = I_5$ whenever the repair on the equipment causes total unavailability of the unit.

These indicators can differ in a significant manner depending upon the maintenance practice, and the degree of urgency associated with the repair.

Since there is clearly a trend with time, values averaged over a number of years must be treated with caution.

APPENDIX III: COMPARISON OF EQUIPMENT DEPENDABILITY INDICATORS FOR FEEDWATER PUMPS

This comparison concerns equipment dependability indicators for feedwater pumps belonging to various feedwater systems of different types and sizes, as outlined below.

Utilities involved

The data on feedwater pumps were collected by the following utilities:

- UTILITY A 28 x 900 MW units from 1983 to 1991 - 224 unit-years
- UTILITY B 990 MW Plant from 1990 to 1992
- UTILITY C 2 x 125 MW Fossil Plants from 1991 to 1992
- UTILITY D Fossil Plants: 4 x 320 MW units from 1988 to 1992

Pump characteristics

- UTILITY A 2 x 65% turbine-driven feedwater pumps, 5270 kW
  Mean yearly operating time 6500 h
- UTILITY B 2 x 80% turbine-driven feedwater pumps
- UTILITY C 3 x 50% motor-driven pumps
- UTILITY D 3 x 50% motor driven pumps

Maintenance indicators

1) Corrective maintenance indicators

Parameter	Utility A	Utility B	Utility C	Utility D
I_1 - Maintenance frequencey (Events/pump x year)	0.5	1.17	1.0	5.6
I_2 - Maintenance effort (Man-hours/pump x year)	56	31.7	44	161
I_3 - Equipment downtime (Downtime/Reference time period, %)	0.23	0.265	0.84	1.24
I_4 - System Function downtime (Function downtime/Reference time period, %)	0.08	0.39	0.02	NA
I_5 - Unit Capability Loss factor (Unavailable energy/Reference energy, %)	8.0 E-2	8.0 E-3	3.0 E-2	NA

Note: UTILITY D data concerns only pump, drive and associated instrumentation

2) Preventive maintenance indicators

Parameter	Utility A	Utility B	Utility C	Utility D
I_1 - Maintenance frequencey (Events/pump x year)	1	1.33	3.8	2.9
I_2 - Maintenance effort (Man-hours/pump x year)	122	295	203	125
I_3 - Equipment downtime (Downtime/Reference time period, %)	1.52	1.32	4.05	1.05
I_4 - System Function downtime (Function downtime/Reference time period, %)	0	0.26	0	NA
I_5 - Unit Capability Loss factor (Unavailable energy/Reference energy, %)	0	0	0	NA

General comment:

In addition to their value for improving maintenance activities within a utility, an important application of the equipment dependability indicators is to facilitate comparisons between different utilities. Where there appear to be significant differences in the values of the equipment dependability indicators between different utilities, detailed investigation is needed to determine the explanation for them. One reason for discrepancies relates to the use of different cut-off levels when recording maintenance activities. Others may relate to the use of different system boundaries or to differences in size, design, or redundancy levels. Most maintenance activities (~ 80%) are relatively inexpensive and may not always be recorded.

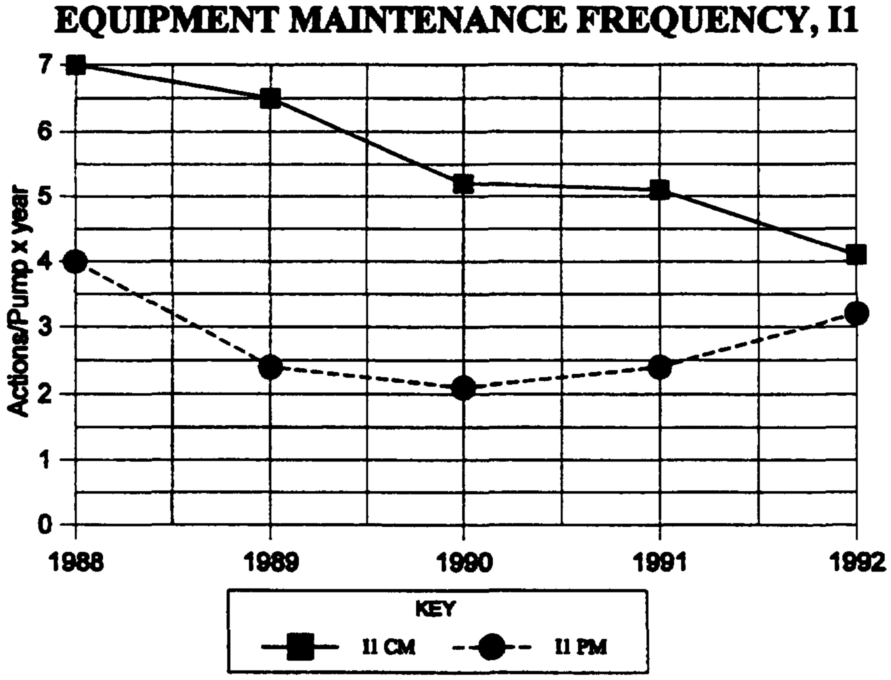
APPENDIX IV: EXAMPLES OF TREND ANALYSIS FOR CORRECTIVE AND PREVENTIVE MAINTENANCE OF TWELVE FEEDWATER PUMPS

This trend analysis is related to the twelve motor-driven feedwater pumps of a fossil power plant (4 x 320 Mwe) over the period 1988-1992.

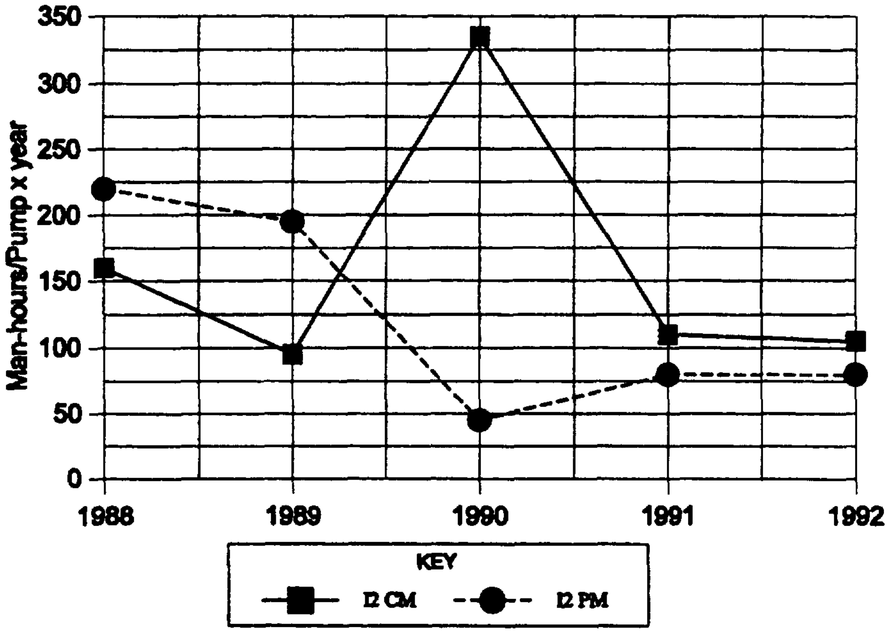
The indicators I_1, I_2 and I_3 show a falling trend both for PM and CM due to both the increased availability of the pumps following initial teething troubles and to an improvement in maintenance planning by the station staff.

The peaks shown in 1990 for I_2 and I_3 are related to a major failure of one of the twelve feedwater pumps that dramatically increased the extent of CM. There was a corresponding reduction in PM because this was conducted in the shadow of the CM.

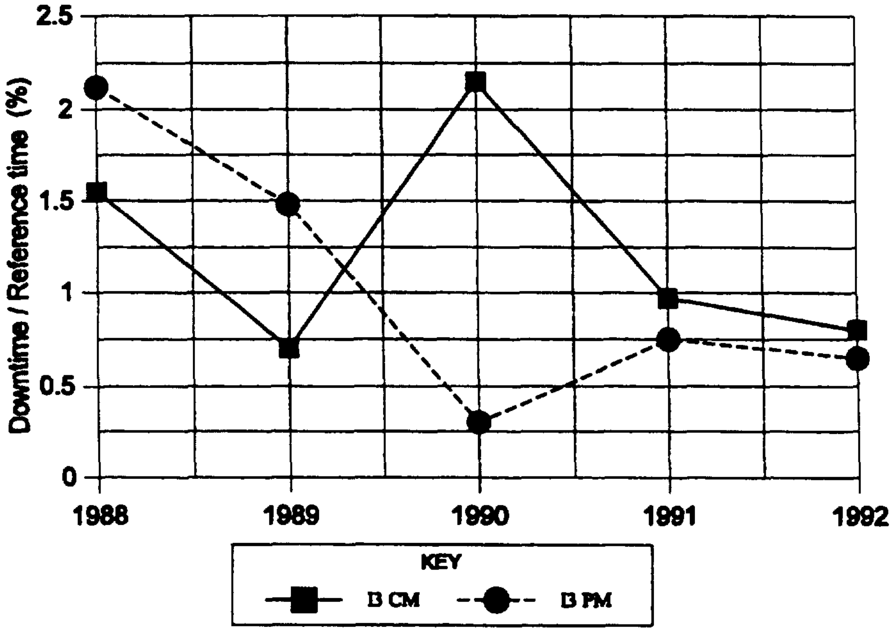
I_4 and I_5 (for PM and CM) are equal to zero for all the periods under consideration.



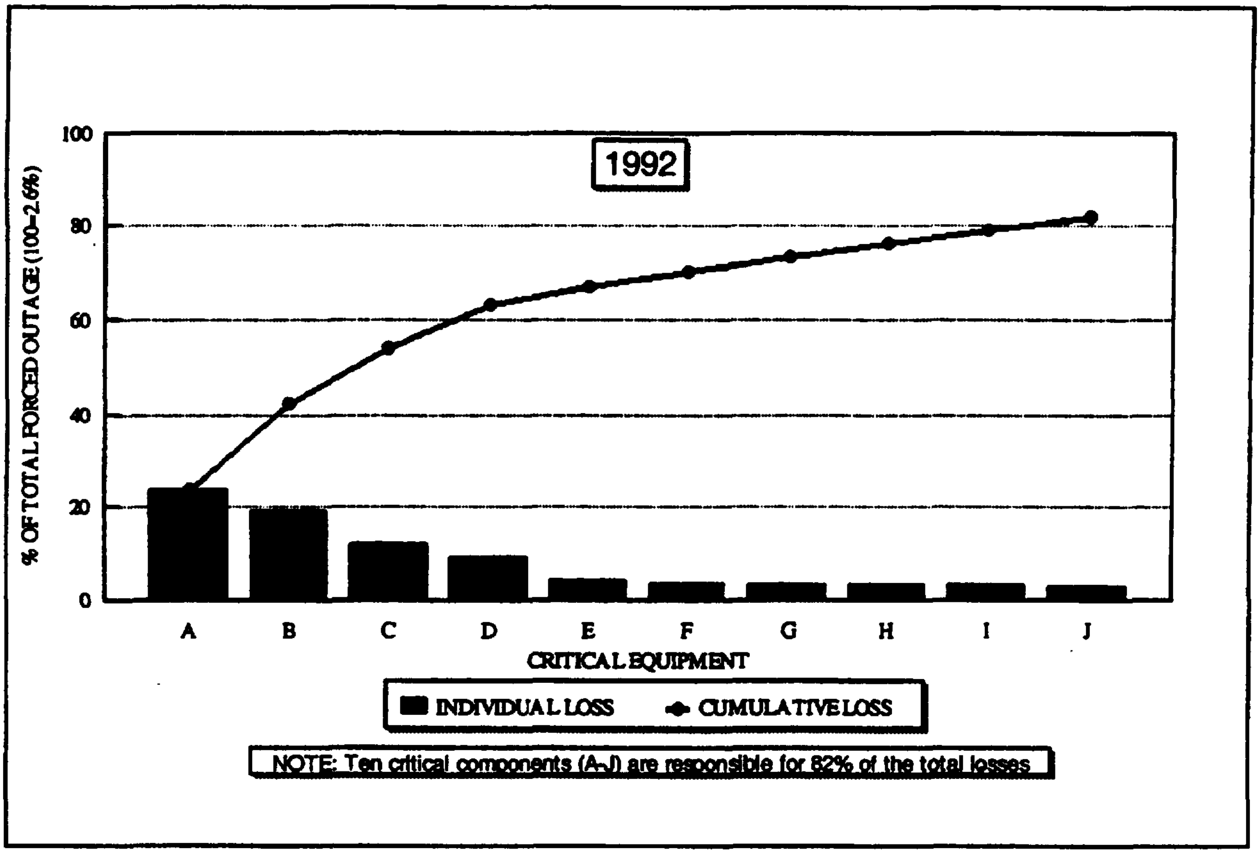
EQUIPMENT MAINTENANCE EFFORT, I2



EQUIPMENT DOWNTIME FACTOR, I3



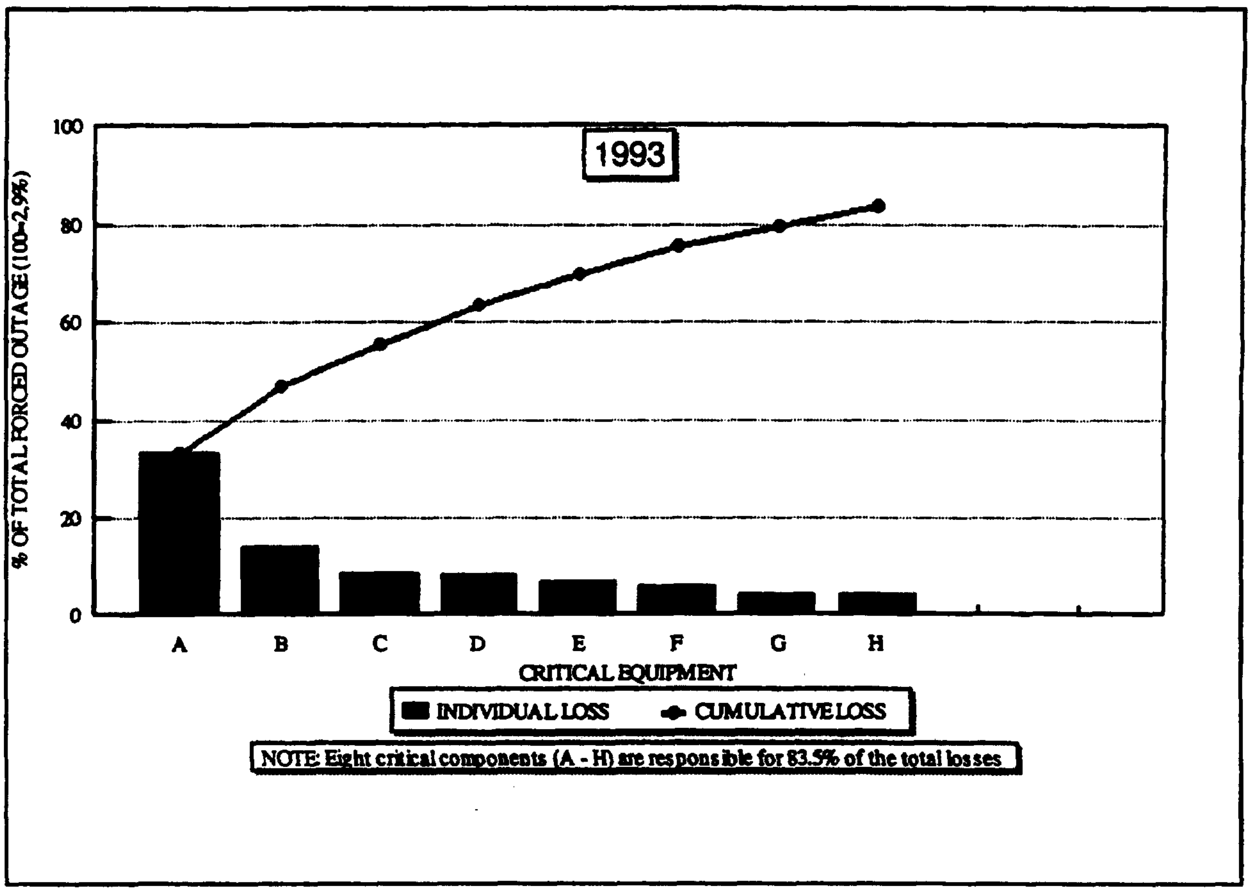
APPENDIX V: INFLUENCE OF CRITICAL EQUIPMENT ON FORCED OUTAGES AT FIVE FOSSIL FIRE POWER STATION (1992-94)



Key to Equipment:

Equipment		Power Station				
		A	B	C	D	E
A	Superheater	X	X	X		X
B	Reheater					X
C	Water wall tubes	X			X	X
D	HP feedwater system & feed heaters	X	X		X	X
E	Refractories & ash tray			X	X	X
F	Turbine control, stop & non-return		X	X	X	X
G	Regenerative air heaters	X	X			
H	Cooling water system					X
I	Main condenser		X		X	
J	Steam drum level indicator	X			X	

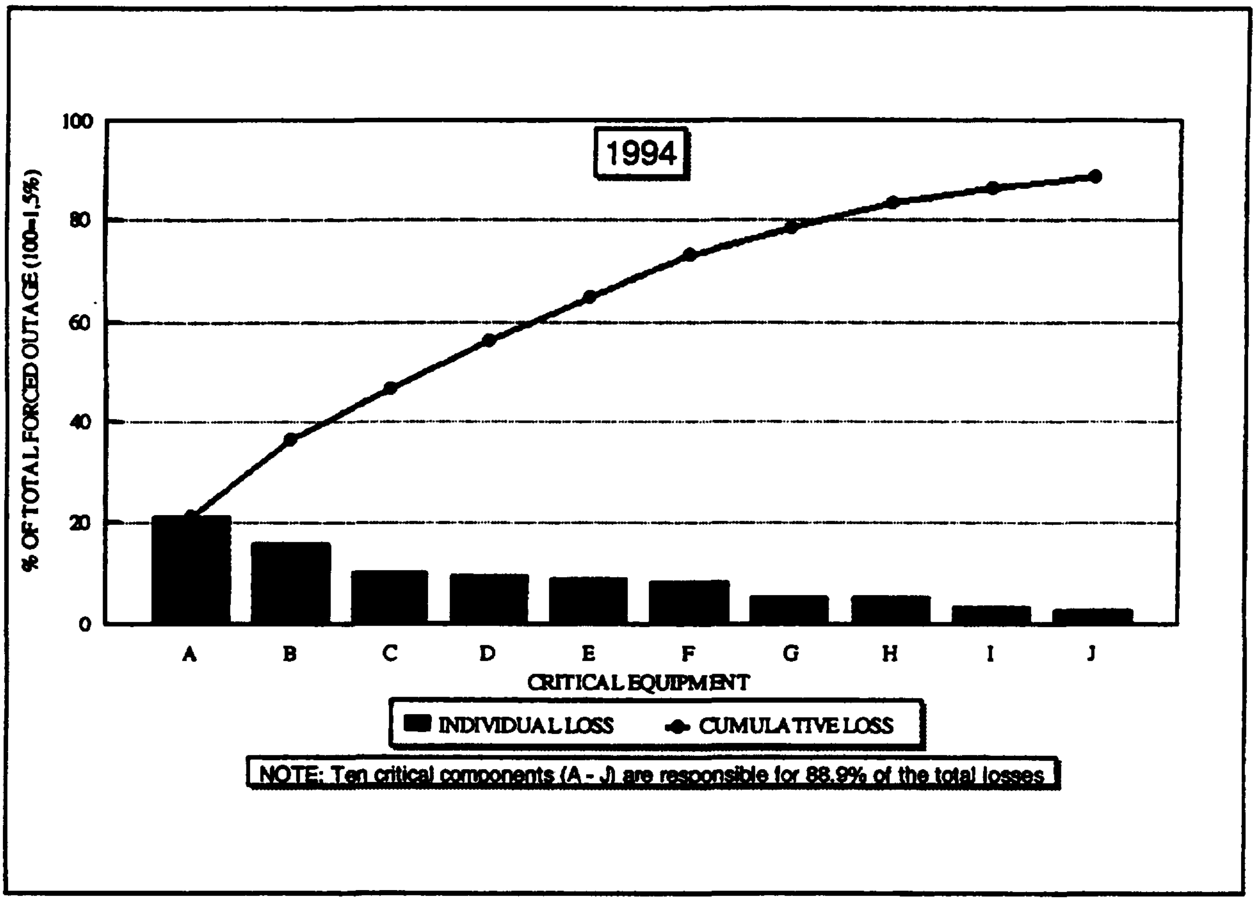
APPENDIX V: CONTINUED



Key to Equipment:

Equipment		Power Station				
		A	B	C	D	E
A	Generator		X		X	X
B	Refractories				X	X
C	Reheater				X	
D	Regenerative & steam air heaters		X		X	X
E	Superheaters	X	X			X
F	HP feedwater system & feed heaters		X			X
G	Economiser	X	X		X	
H	Turbine regulation/control		X			X

APPENDIX V: CONTINUED



Key to Equipment:

Equipment		Power Station				
		A	B	C	D	E
A	Regenerative & steam air heaters		X	X	X	
B	Generator	X	X		X	X
C	Boiler structure				X	X
D	Economiser		X			
E	Superheater & reheater steam pipes				X	
F	Water wall tubes	X	X			X
G	Turbine			X	X	X
H	HP feedwater system & feed heaters	X	X	X	X	X
I	Fuel/coal handling					X
J	Drum	X	X			

Note: the above Tables and Figures present information at the utility level and allow the following conclusions to be drawn:

a) the family of items of equipment responsible for the majority of forced outages at each station changes somewhat from year to year,

b) the relationship between the "size" of these families and the cumulative percentage of the total forced output losses is approximately in accordance with Pareto's law,

c) this approach can be used to pinpoint those critical items of equipment for which systematic analysis of the dependability indicators would be worthwhile.

With regard to availability, the data show that all stations experience considerable trouble with superheaters, the HP feedwater system and regenerative air heaters. However, at the strategic level there is relatively little trouble with cooling water systems.

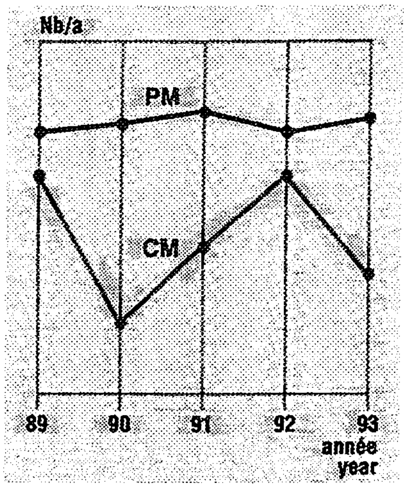
CENTRALES ELECTRIQUES — POWER PLANTS

• COEFFICIENT D'UTILISATION D'UN MATERIEL : Le coefficient d'utilisation d'un matériel est le rapport entre le nombre d'heures de fonctionnement effectif du matériel sur le nombre d'heures annuel.

• EQUIPMENT OPERATION COEFFICIENT: The equipment operation coefficient is the effective number of operating hours of the equipment over the annual hours number.

FREQUENCE DE MAINTENANCE ASSOCIEE A UN MATERIEL, I_1

Le coefficient de fréquence de maintenance (corrective ou préventive) associée à un matériel correspond au nombre d'actions de maintenance réalisées pendant le temps de référence (exprimé par année).*

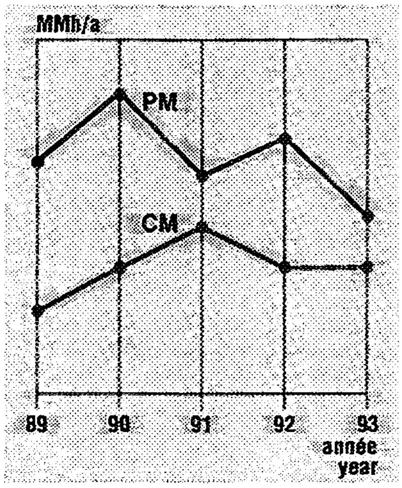


EQUIPMENT MAINTENANCE FREQUENCY, I_1

*The equipment maintenance frequency is defined as the number of maintenance actions per item of equipment (corrective or preventive), per reference time period (expressed per year).**

EFFORT DE MAINTENANCE ASSOCIE A UN MATERIEL, I_2

Le coefficient d'effort de maintenance associé à un matériel correspond au nombre d'heures de main-d'œuvre cumulées effectuées pour la maintenance (corrective ou préventive) (MMh) sur ce matériel, pendant le temps de référence (exprimé par année).*

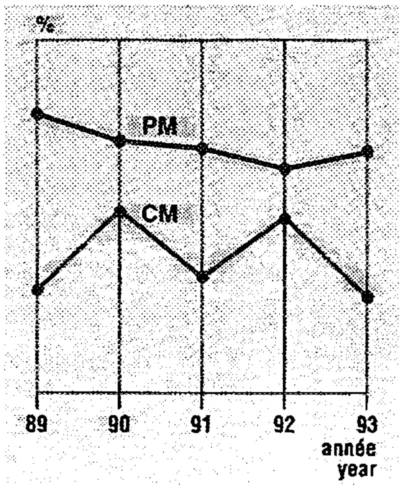


EQUIPMENT MAINTENANCE EFFORT, I_2

*The equipment maintenance effort is defined as the number of equipment maintenance man-hours (MMh) (corrective or preventive) per item of equipment, during the reference time period (expressed per year).**

COEFFICIENT D'INDISPONIBILITE D'UN MATERIEL, I_3

Le coefficient d'indisponibilité d'un matériel correspond au rapport (exprimé en pourcent) entre le temps pendant lequel le matériel est indisponible pour maintenance (corrective ou préventive) et le temps de référence (exprimé par année).*

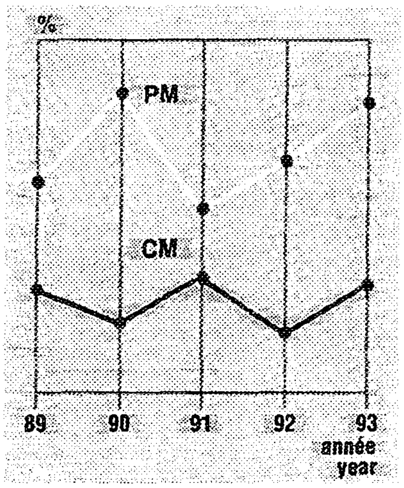


EQUIPMENT MAINTENANCE DOWNTIME FACTOR, I_3

*The equipment downtime factor is defined as the proportion of time a particular item of equipment is unavailable due to maintenance activities (corrective or preventive), expressed as a percentage of the reference time period (expressed per year).**

CONTRIBUTION DE LA MAINTENANCE D'UN MATERIEL A L'INDISPONIBILITE DE LA FONCTION D'UN SYSTEME, I_4

Le coefficient de contribution d'un matériel à l'indisponibilité de la fonction d'un système correspond à l'indisponibilité de ce système due aux actions de maintenance (corrective ou préventive) effectuées sur ce matériel, exprimée en pourcentage du temps de référence (exprimé par année).*

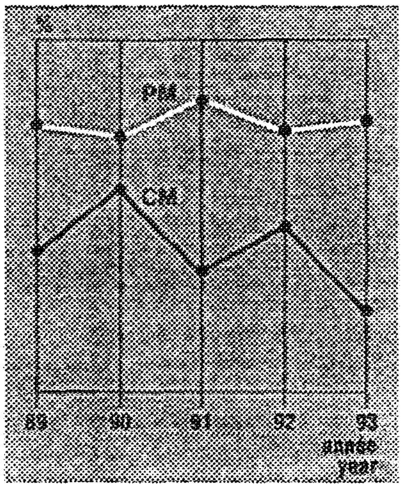


EQUIPMENT MAINTENANCE CONTRIBUTION TO THE SYSTEM FUNCTION DOWNTIME FACTOR, I_4

*The equipment maintenance contribution to the function downtime factor is defined as the system function downtime due to equipment maintenance (corrective or preventive), expressed as a percentage of the reference time period (expressed per year).**

CONTRIBUTION D'UN MATERIEL A L'INDISPONIBILITE DE TRANCHE, I_5

Le coefficient de contribution d'un matériel à l'indisponibilité de tranche correspond au pourcentage de l'énergie indisponible due à des actions de maintenance (corrective ou préventive), effectuées sur ce matériel, par l'énergie qu'il aurait été possible de produire par la tranche fonctionnant dans ses conditions de référence, pendant le temps de référence (exprimé par année).



EQUIPMENT CONTRIBUTION TO THE UNIT CAPABILITY LOSS FACTOR, I_5

The equipment maintenance contribution to the unit capability loss factor is defined as the energy lost due to the unavailability of individual item equipment because of maintenance activities (corrective and preventive), expressed as a percentage of the energy that could have been produced by the unit, operating at the Net Design Rating during the reference time period (expressed per year) had maintenance not been taking place.

SURETE DE FONCTIONNEMENT : l'ensemble des propriétés qui décrivent la disponibilité et les facteurs qui la conditionnent : fiabilité, maintenabilité et logistique de maintenance.

DEPENDABILITY: is the collective term used to describe the availability performance and its influencing factors: reliability performance, maintainability performance, and maintenance support performance.

* Le temps de référence est la période pendant laquelle le matériel est fonctionnellement requis pour la production ou pour une fonction de sûreté : le temps de référence est normalement l'année calendaire (8760 h). Cependant toute autre période adéquate peut être utilisée à condition qu'elle soit suffisamment longue pour être significative et qu'elle soit normalisée en terme d'années. Lorsque les matériels sont redondants, on utilisera le temps équivalent annuellement requis par matériel.

* *The reference time period is the period during which the equipment is needed for its production or safety functions: the reference time period is usually taken to be one year (8760 h). However, any other suitable period can be used as the reference time period provided that it is long enough to have some significance and that the dependability parameters are normalized in term of years. For redundant equipment, the equivalent yearly running time per equipment will be used.*