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Consolidated Fuel Reprocessing Program

RELIABILITY AND MAINTAINABILITY DATA ACQUISITION IN EQUIPMENT DEVELOPMENT TESTS

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HIGHLIGHTS

The need for collection of reliability, maintainability, and availability data adds a new dimension to the data acquisition requirements of equipment development tests. This report describes the reliability and maintainability data that are considered necessary to ensure that sufficient and high quality data exist for a comprehensive, quantitative evaluation of equipment and system availability. These necessary data are presented as a set of data collection forms. Three data acquisition forms are discussed: an inventory and technical data form, which is filed by the design engineer when the design is finished or the equipment is received; an event report form, which is completed by the senior test operator at each shutdown; and a maintainability report, which is a collaborative effort between senior operators and lead engineers and is completed on restart.

In addition, elements of a reliability, maintainability evaluation program are described. Emphasis is placed on the role of data, its storage, and use in such a program.

1. INTRODUCTION

Probabilistic risk assessment (PRA) techniques have been used successfully in studies when the objective is to make a choice between the safer (or more reliable) of two designs. Numerous examples exist which tell of PRA providing guidance in designing a system (e.g., helping to select the component or system assemblages of lowest risk). The worth of the technique is generally acknowledged when a choice must be made from among two or more systems which perform the same functions (i.e., when relative values are the product of the evaluations). Technique logic models such as event trees and fault trees can be, and are, resolutely defended.

Now pressures are being exerted to apply the PRA techniques to arrive at absolute numerical values which indicate that a design, safety, or perhaps even a licensing goal will be satisfied. This modest extrapolation of past successes seemingly requires only the application of failure and maintenance data input to established methods. However, this extrapolation is viewed with some apprehension because of the low quality of the basic data. For example, the U.S. Nuclear Regulatory Commission is engaged in an extensive study to establish mathematical techniques to handle the propagation of data uncertainties. Basic failure and maintenance data are the weak links of the PRA or reliability analysis. A number of data bases exist, yet there is often insufficient detail to determine failure rates for specific items. The alternative is to resort to generic data of "like" items since test programs are too expensive for all but the most important equipment. A search through data bases indicates, however, that failure data varies over wide ranges of values from source to source for apparently identical equipment. This variability results, in large part, from incomplete recording of the pertinent information (e.g., operating environment) required for a complete characterization of the failure or maintenance event.

Sources of much of these data are the operating records of a facility or test programs. Trying to glean detailed information from operation reports long after completion of operation or testing is futile. At best such data are of low quality and much information is lost because of oversight or from a lack of knowledge of what is important.

During the course of developing a failure and maintenance testing program for the Consolidated Fuel Reprocessing Program (CFRP) at the Oak Ridge National Laboratory, we concluded that to be most effective the data acquisition program must be defined before the test program actually begins. This conclusion required that the equipment, the system, the operating environment, and other system characteristics of importance be identified in advance; that the proposed method of data analysis be defined; and that data acceptance criteria be established.

This paper outlines the reliability and maintainability data that are considered necessary to ensure that the proposed comprehensive, quantitative evaluations of equipment and system availability will be of sufficiently high quality that design and flowsheet decisions can be made with confidence. System availability will be calculated during and following the test program using the accumulated reliability and maintainability data. These necessary data are presented in this paper as a set of data collection forms. These forms are designed to serve as a guide and can be tailored to any particular data acquisition or reporting program. The data to be collected by the reliability engineer can be acquired in three related recording sessions.

2. SUMMARY

Quality data acquisition from equipment development and systems integration test programs have long been recognized as a most important part of a good research and development (R&D) program. Unfortunately, most data acquisition plans for R&D programs have not considered the collection of data required to support a reliability and maintainability data base.

Reliability and maintainability data are acquired by monitoring the whole array of experiences from component development testing to facility operations. The data acquisition program must be defined before it begins: the characteristics of interest identified, the method of data analysis defined, and data acceptance criteria established. Data requirements are frequently stated in terms of confidence levels. The statistical analysis of data and discussions of the design of engineering experiments are beyond the scope of this work.

Sources of data are the same in all cases, the operating records of a facility or tests. However, efforts to glean detailed information from operation reports, long after tests are complete, are futile. At best, such data are of low quality. Also, data are lost because of oversight or from a lack of knowledge of what is important. To rectify this, a set of data collection tables have been developed which, if followed, will be sufficient to lead to the preservation of the necessary reliability and maintainability data required as input for systems availability analyses. This report describes the information required for reliability, maintainability, and availability analyses.

The data to be collected may be acquired in three related data recording sessions. The first of these recording sessions should preferably be done when the equipment items are in the final stages of construction or upon receipt and checkout of the items. The "Item Inventory and Technical Data" table is completed for each equipment item to the level where repairs or replacement with spare parts are made. It contains a complete description of each equipment item to be tested and of the conditions under which it is expected to be operated.

The second data collection period follows each significant interruption in the test program and is reported in the "Event Report." This report is considered the principal reliability data form. The event report contains not only failure events from which failure rate data are required, but also provides a history of related actions taken during the test program. Scheduled preventive maintenance shutdowns and equipment calibrations are examples of these related actions.

The third data collection period occurs at the end of each recovery from failure, or scheduled shutdown, with the completion of the necessary maintenance and the return to normal operating conditions. This is recorded as "maintainability data." Maintainability data for an equipment R&D program must discriminate between prototypic and nonprototypic equipment. However, in a system integration test, each failure and completed maintenance action, whether on prototypic or nonprototypic equipment, can provide useful design information. To discriminate between the maintenance data on prototypic and nonprototypic equipment, separate maintenance data forms are recommended. The maintenance data form for the nonprototypic equipment may be less comprehensive than that for prototypic equipment.

On each maintenance data form, information on the distribution of downtime (i.e., the detection, diagnosis, correction, verification, administrative, and logistics times) is required. In addition, a classification of the fault and description of the failure are needed. For prototypic equipment more detail is required, and considerations of preventive maintenance, fault correction, adequacy of maintenance procedures, feedback to design, and human factors are included.

3. ELEMENTS OF A RELIABILITY AND MAINTAINABILITY PROGRAM

This chapter describes the constituent parts of a reliability and maintainability program to predict a facility's availability. Also, the role of data acquisition and the flow of accessed information and data are discussed.

3.1 Availability Prediction and Allocation

The parameters – reliability, availability, and maintainability (RAM) – are related by the equation:

$$\text{availability} = \frac{\text{up-time}}{\text{mission time}}$$

$$= \frac{\text{meantime between failures}}{\text{meantime between failures} + \text{time to repair}}$$

Thus, availability is the probability that a system failure does not exist at some specified time within a mission. Reliability is the probability that a system will perform a required function for a stated period of time and is determined from the failure frequency. Maintainability is the probability that a system can be repaired in a stated period of time. Figure 1 relates these three principal parameters to other activities of a reliability and maintainability program.[1]

Overall system characteristics, including reliability and maintainability, must be translated into detailed design and operating specifications. The process of assigning reliability and maintainability requirements to individual components to attain the desired system availability is known as availability apportionment. The availability of an individual component varies with the type of function to be performed, the method of accomplishing the function, the complexity of the unit, the maintenance concept, the available diagnostics, accessibility to the failed unit, and skills and experience level of the maintenance personnel.

Allocation of system availability is the inverse process to an availability prediction.[2] In a prediction process, measured or estimated *mean-time-between-failure* and *mean-time-to-repair* of parts and subsystems are used as the basis for computation of system availability.

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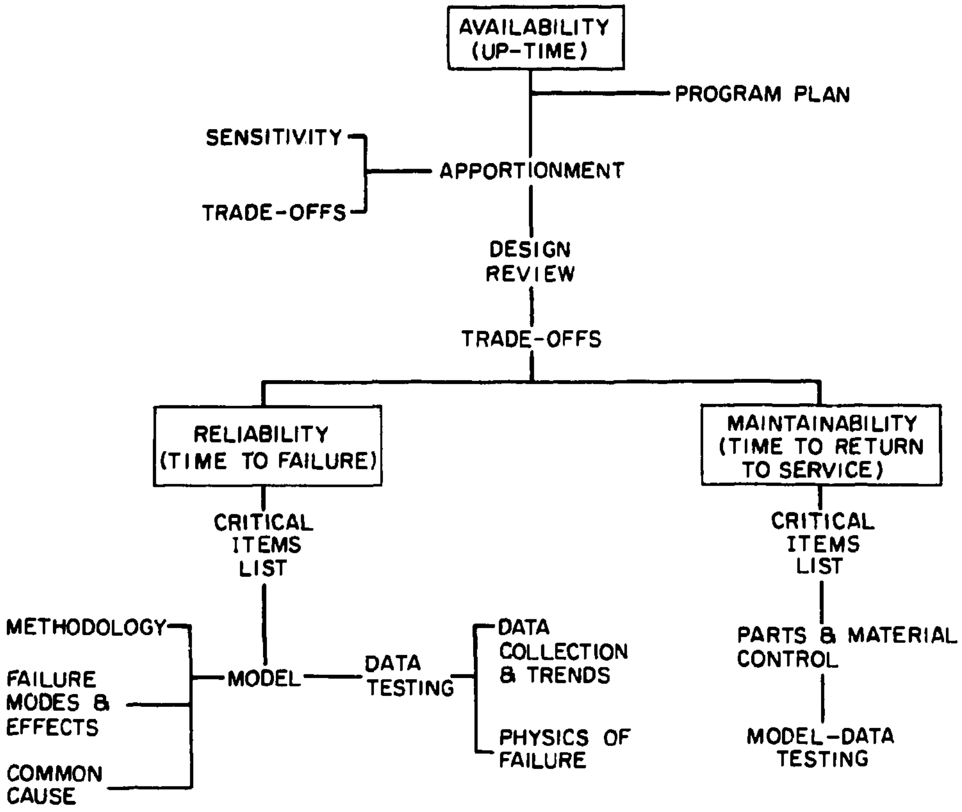

Fig. 1. Principal elements of a reliability and maintainability program.

In an allocation, the process starts with a plant requirement (or goal), which is converted to an availability goal permitted for each system. Each system's goal is then allocated between its various subsystems. The apportionment in no sense indicates that the particular level of availability can be achieved. It merely means that if the apportioned values are achieved, the system will meet its goals or requirements.

One of the earliest analytical activities of a reliability and maintainability program is to apportion the overall facility availability goal between major systems that contribute toward the total goal. For the initial apportionment, the availability allocation model usually employs a "top-down" approach and is not as detailed as a prediction model, based on system fault tree and equipment maintainability analyses. Rather, the initial facility availability allocation is carefully performed using expert opinion. As the system design matures and as detailed prediction models are developed and experimental data become available, a comparison must be made between the allocated system availability and the current assessment. Thus, through an iterative process, discrepancies between the facility component availability goal and predicted availability are resolved so that the overall facility availability criteria can be met. This process is shown schematically in Fig. 2.

In apportionment and trade-off studies, the overall goal is allocated in a manner that will optimize some other important parameter, such as total cost. Trade-off studies are

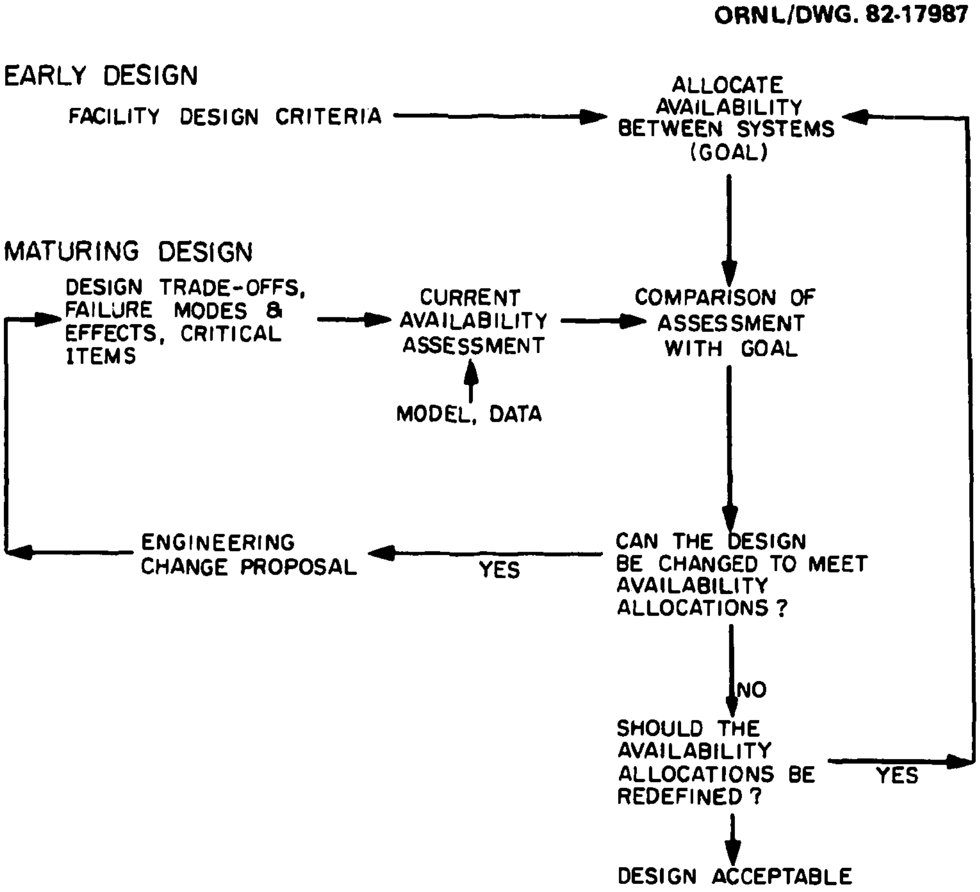

Fig. 2. Availability assessment flow.

used to maximize the probability of success within certain constraints such as cost, equipment, or schedule limitation or to resolve conflicting goals, such as a conflict of a safety-related reliability goal with an operating plant availability goal. Apportionment and trade-off studies are best done early in the design stage while configuration changes are possible. Unless this preliminary work is done, stated reliability and maintainability goals may not be compatible with the required systems configuration and the state of the art. On highly developmental systems, configuration changes occasionally occur late in the design cycle as a result of unforeseen difficulties in hardware or process development.

Sensitivity studies are done to identify critical items and areas of overconservative designs that are not cost-effective.[1] They may be used to optimize goal apportionments or trade-offs. After the design configuration is firm, sensitivity studies may be used to determine surveillance intervals, appropriate stocking levels of spare parts, and optimization repair activities.

The allocated overall facility availability goals are given to functional task leaders. It is the responsibility of task leaders to decide how to meet their system availability goal. After conducting a trade-off evaluation, a task leader may prefer to emphasize high equipment reliability (infrequent failures). Infrequent failure occurrences provide longer time to recovery from failures. Conversely, for the same availability goal, the task leader may choose to have easily maintainable equipment and thus have the capability of rapidly returning failed equipment to service. Higher failure rates may be tolerated if failed equipment can be returned to service rapidly. Equipment functional requirements and design and operating environments may indicate preference for either a high reliability or high maintainability approach.

3.2 Reliability Assessments

Reliability studies are concerned with predicting equipment failure rates.[3] System design is frequently complex and involves a large number of interacting parts, each with a probability of failure. As a result, sophisticated computerized models have been developed which quantify system reliability. The predicted reliability is only as good as the data input to the calculations and the depth of the associated supporting analyses. An important output of the predictive reliability model is a prioritized list of weak links or critical items list in a system.

The identification of critical items from the standpoint of reliability and maintainability, in the system design, is an excellent way to bring their importance into focus. The earliest identification may be purely qualitative, perhaps derived from a failure mode and effects analysis, or from a projected critical path maintenance path line. The critical items list helps identify where requirements specifications should be made in the system design criteria. The list is periodically updated as the design progresses, as test results become available, and as further studies are performed.

The critical items list is a valuable management tool, allowing the project manager to deal with the most important development problems. The list simply reflects that state of knowledge at a given point in time. It is one of the least expensive and highly visible activities of a reliability and maintainability analysis program.

In predicting availability, the analyst develops a system model utilizing information such as failure rates and repair times. This model shows the interrelationships between the items that make up a system, the attendant response to failure, and the repair times. A model is exclusively directed at one definition of system success (or failure). For this reason, a different model is required to conduct each specific study. For example, a model for a safety-related system may show high-level redundancy so that many items may fail without a failure of the system's safety-related function. On the other hand, the same system modeled for operating availability may reflect a requirement that the plant be shut down for the failure of safety-related components. The items shown as being redundant in the safety-related reliability model become individual single failure points in the operating availability model. Sometimes, a flexible model can accommodate multiple definitions of system success; however, this may complicate the analysis.

There are many equivalent ways to model a given system, some of the most popular being event-tree analysis, fault tree analysis, reliability block diagrams, truth (or state) tables, and Markov-state diagrams. Any method which depicts relevant information in a form that is condensed, logical, and accurate could be acceptable. However, in addition to being a simple and compact representation of the system and how it works, the model is frequently used as a direct input to a computer program for prediction computation. Such models are required in trade-off and sensitivity studies.

A failure modes and effects analysis is the basis for many reliability engineering tasks.[1] This analysis, by evaluating the mode of failure and the effect of failures on the system, supports appropriate studies in safety-related reliability, operating plant availability, and maintainability. It provides the information needed to prepare a model and carry out apportionment, trade-offs, and sensitivity studies. Top- or system-level failure modes and effects analyses are performed to evaluate the consequences of system level failures. Lower level analyses are performed to evaluate the consequences or lower tier failure and may only be justified when the system level failure consequences are unacceptable. The failure modes and effects analyses are frequently a joint effort linking the design engineer with the reliability engineer. The reliability engineer can contribute a format and a discipline for the study, and ask key "what if" questions probing for failure modes and mechanisms. The design engineer contributes his detailed knowledge of the component system, how it functions, and how it copes with failure. The result can often be a more thorough probing than could be done by either engineer alone, plus a greater transfer of knowledge and perspective across the normal disciplinary boundaries.

Early in the design cycle, a qualitative common cause failure analysis establishes the need for diversity, separation, or isolation of critical components. After components are selected and system layouts established, the common cause analysis may focus on causes such as common history, environment, and external events that link failures of seemingly independent components. Finally, before system startup, the common cause failure analysis may focus on procedures, training, and operational human factors. In the main, common cause failure analyses are qualitative in nature, although some computer-aided search programs have been devised.

Reliability data are obtained from manufacturers, from generic data bases such as the Government Industry Data Exchange Program (GIDEP),[4] from tests planned primarily for other purposes (e.g., functional testing), and from expert opinion. Functional testing of prototype equipment may not yield significant reliability data: failures that do occur will likely result from infant mortality or from design faults. Criteria must be established for data acceptability. For example, it may be decided that only random failures (failure events from that period after infant mortality but before aging) are of interest. Data requirements should also be expressed in terms of confidence bounds - the probability that a value of a parameter lies between two extremes. The ultimate objective is to propagate upper and lower bounds of parameter values from the part level to the systems level. Such a statement would have the form "the system will have an availability of at least $X\%$ but not more than $Y\%$ at a $Z\%$ confidence level.

Tests are especially designed for obtaining reliability and maintainability data because of (1) incompleteness and (2) the wide margin between upper and lower bounds of the data. It is impractical to conduct a reliability testing program for all parts contained in a system. Most equipment parts have low failure rates; therefore, long test periods and/or large numbers of items tested are required before a statistically acceptable number of failure events are on hand for use in reliability analyses. Accelerated life testing methods[5] with sophisticated environmental sensitivity testing may be needed. These testing and data acquisition programs are costly. Therefore, test programs need to be meticulously planned and the perceived benefits balanced against the cost before the program is undertaken. Since testing programs cannot be conducted for every part, only those parts on the before-mentioned critical items list should be considered for reliability testing. Sensitivity and trade-off studies – design review (see Fig. 1) and design criteria–culminate in a list of equipment items that require reliability and maintainability test programs.

The methods of data analysis and the interpretation of data that may be obtained from the test should be established before the test program is conducted. Data acceptance criteria must be established in testing programs set up to obtain reliability and maintainability data. The characteristics of interest are measured to a certain confidence level. Confidence level requirements establish how much data are needed, or alternatively, how many failure events are allowed before an apportioned availability goal is reached and still have the item considered acceptable. If tests are run that are limited and cannot provide the necessary data, then some notation to this effect should be made so that valuable time will not be wasted collecting data which has no planned use. The testing program, the data analysis, and the data acquisition forms and procedures (a generic example is presented in this report) should be tailored to each particular circumstance. Reference 6 gives a thorough discussion of the statistical design and analysis of engineering experiments.

Physics of failure studies play a significant role in developing an acceptable hardware system. In the development phase of a design, failure mechanisms should be hypothesized and categorized as to which ones are significant. When the design has been reduced to hardware, the failures should be thoroughly analyzed to establish, with some certainty, whether a basic defect supports the failure modes and effects analysis and the common cause failure analysis.

Basic data on failure rates and modes and repair times are essential to predictive availability analysis. Related information from sources outside one's own testing program must be collected and analyzed for trends which may become the basis for initiating corrective action programs. Since the equipment is often similar or identical to equipment already being supplied to others, data obtained from generic data bases and existing field applications may be analyzed and the results applied to the test program of interest.

3.3 Maintainability Assessments

Maintainability studies are concerned with predicting repair rates.[7,8] The discussion in the previous section regarding model development and the critical items list associated with reliability prediction also applies to maintainability. It may be necessary to generate a model, use it to make a prediction, and follow with trade-off and sensitivity studies.

The results of a maintainability study are useful in establishing the requirement for access to equipment and in determining space requirements for disassembly, access to hoists, and protective radiation shielding. The ideal maintainability analysis should be started early enough so that these results can influence plant layout. The maintainability analysis may also deal with the need for special tools, availability of replacement parts, and training requirements of maintenance personnel.

Maintainability data of prototypic equipment can be easier to acquire and more representative than reliability data. In maintainability tests of prototypic equipment, representative faults, identified by reliability modeling and predictions, are simulated. Repair of the simulated fault can be done by technicians to give a repair time density distribution. Repair times and the associated analysis of the tests are more brief than testing the prototypic equipment to failure.

Repairs can be made rapidly if spare parts are on hand. If a replacement part is needed but is not available, long downtime can result. For example, some industry-standard parts must be ordered far in advance because they must be manufactured. Maintaining the most cost-effective inventory of spare parts for a facility requires (1) identification of the most needed parts, (2) an analysis of the associated risk of not maintaining a part as a spare, and (3) warehousing it and properly coding it.

One way of increasing chemical plant availability is to place a surge capacity between principal components that are in series. Thus, if the component in question fails, the facility can continue to operate until the material in the surge tank is depleted, or until the surge tank upstream of the failed component fills to capacity. If the component can be repaired in the time interval between emptying or filling these surge tanks, the plant production line will not have to be closed down. Optimization of this problem requires a sophisticated analysis considering flowsheet optimization, equipment reliability and maintainability, warehousing of spare parts, and cost trade-offs between the various options.

4. INVENTORY AND TECHNICAL DATA BASE

It is important at the outset of a testing program to uniquely identify all equipment items on which data is to be collected and recorded. Normally, items will be small assemblies such as pumps, motors, and valves, but they can be smaller components such as bearings and glands. The limit of resolution for item data collection usually extends to the level at which repair is to be made. For example, if the repair policy for a failed electrical motor is to replace the motor rather than to replace the windings or the brushes, the smallest item on which data is collected in the test is the motor. In all cases, a small amount of basic information on each inventory item is required. In addition to each inventory item being uniquely identified by number, it should be characterized by manufacturer, size, and type. Table 1, the Item Inventory and Technical Data, is designed to facilitate the collection of these data.

A baseline technical data set of operational and design specifications must also be available for comparison to data of the component in the failed state, should failure occur. This set is as important as the inventory list. Table 1 shows a data form with 17 fields of required information, ranging from inventory numbers and environmental and operating limits to failure rates and failure rate distributions.

The item inventory and technical data base form is completed before acceptance of the equipment undergoing tests. It is completed by the lead design engineer or senior operator. This form is filled out only once, then is filed in a data bank, ready for retrieval and use as input data to failure analysis in equipment modification, maintenance, or calibration events. Some information for completing this form can be obtained from manufacturers or generic data bases.

Table 1. Item Inventory and Technical Data

---

1. Inventory No. 2. Serial No.

3. Item description

4. Location

5. Manufacturer

6. Design 7. Design year

8. Commissioning data 9. Entry date year

10. a. Number of similar items in system?
    b. What are the inventory numbers of these items?

11. Material of composition

12. Environment design envelope specifications:

    Temperature Vibration
    Humidity Corrosion
    Grit/dust Radiation

13. Design fabrication quality

    ☐ very high standard (e.g., military spec) ☐ high standard (e.g., enhanced, general industry) ☐ general industry ☐ unknown

14. Recommended maintenance interval

15. Average number of cycles/h of operation, if item has intermittent operation characteristic (switches, valves, etc.)

16. Estimated failure rate:

    16a. manufacturer one/hour: mean_____ upper_____ lower_____
    failure distribution: ☐ binominal, ☐ Poison, ☐ exponential ☐ unknown

    16b. generic literature sources one/hour: mean_____ upper_____ lower_____
    failure distribution: ☐ binominal, ☐ Poison, ☐ exponential ☐ unknown

17. Operation design specification limits (e.g., pressure, flow rates, temperature, speed)

    17a. 17d.
    17b. 17e.
    17c. 17f.

Submitted by ____________________________ Date____________________

5. THE EVENT REPORT

In completing the event report, every shutdown event on every equipment item tested is recorded, not just the failure events. Thus, if an instrument is recalibrated, that action must be documented. If the equipment is modified or if preventive maintenance occurred, this too must be recorded. If, for example, the fact that an equipment item is rebuilt but is not recorded, the reliability data collected on that item is worthless. The objective is to have at the end of the testing program a history of every event action conducted on every test item.

Table 2 lists possible types of events and collects the necessary information concerning the event. The form is completed at the time of equipment shutdown by the senior operator.

One event of particular interest results from item breakdown or failure. Table 2, the reliability data collection form, identifies the item which failed and its operating time or number of cycles. The fault classification (infant mortality, design, random, etc.) is recorded on completion of the analysis of the failure report.

There are degrees of completeness to what is loosely known as reliability and maintainability data.[8] The basic data source is always the system of recordkeeping describing the operation maintenance activities of a given facility. Usually, data management systems are not specifically designed for reliability and maintenance data needs, although some information is almost always available from operation reports. In these recommended forms, only the information that is likely to be needed is requested, though it is understood and accepted that the amount and quality of information actually received may vary a great deal. A high quality, specifically designed data collection system is required for extensive, detailed facility availability analyses.

It is important to recognize the quality of information for what it is, whether complete or only partial. There are three grades of refinement of data. The "basic grade" of data requires only that the failed item be identified and that its time of operation or number of cycles and the number of failures or breakdowns in the period be known or available. This information will enable a failure rate of the item to be calculated. Note that this basic grade takes no account of the qualifying conditions (e.g., environment) that may affect the behavior of the item. The minimum information for the basic grade is (1) inventory number, (2) item name and description, (3) number of similar items being tested, (4) operating time (cycles), and (5) the number of item failures during the mission. This is the grade of data obtained by reviewing facility past operating reports.

The additional information needed for "intermediate grade" data is (1) the manufacturer; (2) equipment quality; (3) the component material, if relevant; (4) operating environment; and (5) the date of manufacture and entry into service. Note that some qualifying information has been introduced to differentiate between the performance of superficially similar items which may differ in age, environment, or manufactured quality. The inclusion of information concerning the item operating environment is useful in common cause failure analysis.

In "high grade" reliability data collection, one is no longer interested in just breakdown or failure information. Now, "event" information is important. An event can be in-situ maintenance, workshop maintenance, testing and calibration, and equipment modification. In addition, it is useful to know certain facts associated with these events: (1) the routine maintenance interval; (2) the effect on the system of item failure; (3) the effect of item

Table 2. Event Report

---

1. Installation
2. System
3. Item description
4. Event description
5. Report No.
6. Date of event
7. Time of event
8. Item inventory No.

---

9. Item operating time

   a. Total number of operating hours since item installation ________

   b. Estimated total number of cycles* since item installation ______ or, since this item's last event report number ________

10. Method of determining elapsed time (cycles):

    ☐ clocktime ☐ test intervals ☐ elapsed time clock/cycle counters

11. Event type:
    - ☐ breakdown/failure
    - ☐ modification
    - ☐ test calibration
    - ☐ in-place maintenance
    - ☐ workshop maintenance
    - ☐ simulated maintenance test
    - ☐ other ____________________

(Answer questions below that correspond to event type)

A. Breakdown/failure

a) What happened? Why was the system shut down?

b) Operating parameters (e.g., pressure, flow rate, speed at time of failure):

1.
2.
3.
4.

c) Did item operate outside environment design envelope limits?

Temperature ☐ yes ☐ no
Humidity ☐ yes ☐ no
Grit/dust ☐ yes ☐ no

---

*Cycle is any intermittent operation (e.g., stops, starts: valve operation, switch operation).

Table 2 (continued)

Vibration	☐ yes	☐ no
Corrosion	☐ yes	☐ no
Radiation	☐ yes	☐ no

B. What modification was required and why?

C. What test/calibration was required and why?

D. What in-place maintenance was required and why?

E. What workshop maintenance was required and why?

F. What simulated maintenance was conducted and why?

G. Explain "other" category.

12. Effect on system performance
    - ☐ no loss
    - ☐ partial loss
    - ☐ total loss
    - ☐ other

13. State of system when event occurred
    - ☐ startup
    - ☐ operating
    - ☐ shutdown

14. State of installation when event occurred
    - ☐ startup
    - ☐ operating
    - ☐ shutdown

Submitted by ______________________________ Date _________________ failure on plant or installation; (4) the operating conditions at the time of failure (as opposed to design conditions); (5) replacement parts; and (6) the number of failures, the mode of failures, and the cause of failure, and (7) the outage time for each event.

It is clear that Table 2 is incomplete without the data presented in Table 1. Furthermore, Table 2 is missing some key information, for example, the space parts, outage time, and the fault classification, which is requested in the maintainability data collection forms.

6. MAINTAINABILITY DATA FORMS

Just as reliability is a discipline unto itself, so is maintainability with its own more diversified elements. The difficulty of reliability as a subject area is undeniable; reliability deals with the quality of equipment parts, component lifetimes, fail-safe design redundancy, and the dependability of standby safety systems. These problems are, for the most part, quantifiable and measurable during equipment laboratory testing and field operation. Maintainability, however, is unique in every application (e.g., the access space for repair will vary from plant to plant).

The human element is nearly always present during the fault correction process.[9] The interaction of humans with equipment systems is not as quantifiable as the physical aspects of equipment design. Variables in the maintainability discipline must be identified and measured to systematize the equipment design and facility operation process.

The primary variable of interest in maintainability analysis is the time interval between incipient failure and the return to normal operating conditions. This downtime is controlled by a number of parameters in each of three broad areas: the design of the equipment system, the skill of the technician, and the maintenance concept and policies. Obviously, there are many trade-offs and a host of alternatives among many variables in the pursuit of an optimal system design.

This section presents a format for collecting data on maintainability. The data forms contain a comprehensive list of parameters whose values must be known to completely quantify maintainability.[7,8]

6.1 Maintainability Short Form

The extent of maintainability data collection for an R&D program depends on the type of equipment and the test being conducted. An abbreviated maintainability data form (Table 3) is recommended for all events involving nonprototypic equipment and maintenance procedures. Nonprototypic equipment is present as auxiliary support equipment in a test of prototypic devices. Likewise, nonprototypic maintenance procedures may be used during the debugging or shakedown phase of prototypic equipment installations. For example, contact maintenance procedures may be used on nonprototypic equipment during the shakedown phase, whereas remote maintenance techniques must be employed in a radioactive environment. Extensive maintenance data collection may not be worthwhile in these situations, although certain key information is required for the sake of completeness.

Table 3 lists the required summary maintenance information. The total downtime and its constituent elements are requested. The accessibility to the equipment part in question is noted. If the shutdown is due to a breakdown or failure, the fault must be classified, a description of the failure written, and the repair policy noted.

Table 3. Summary maintainability data for nonprototypic equipment

---

1. Installation
2. System
3. Item description
4. Event description
5. Report No.
6. Date of event
7. Time of event
8. Item inventory No.

---

9. Total downtime interval

10. Estimate increments of downtime.

    a. Activity repair/maintenance time

       1. Detection time interval
       2. Diagnosis time interval
       3. Correction time interval
       4. Verification time interval

    b. Administrative time interval

    c. Logistics delay time interval

11. Was there adequate accessibility, work space clearances to failed parts, test points, adjustments, and calibrations? ☐ yes ☐ no

    Comment:

12. Complete the following if the shutdown event is due to a breakdown/failure:

    a. Fault classification

       ☐ Break-in
       ☐ Design fault
       ☐ Random
       ☐ End of design life

    b. Description of failure

       1. What was the defective item?

       2. How was the fault detected?

       3. What was the method of diagnosis?

       4. Briefly describe diagnosis.

Table 3 (continued)

13. Fault correction policy if shutdown is due to failure

    a. Disposition of failed item

    ☐ repair ☐ replace with spare, repair item ☐ replace with spare, discard

    b. Repair location

    ☐ in place ☐ lab bench, hot cell ☐ lab bench, cold cell ☐ factory

Submitted by ________________________ Date ________________

6.2 Maintainability Long Form

Extensive data must be collected for maintenance demonstration runs. Table 4 presents the format for this data acquisition. Maintainability data forms are completed as normal operation is resumed and are filed by the lead engineer and technician who performed the analysis and conducted the repair.

The heading of the maintenance forms is the same as that of the event report. This sameness ensures an irrefutable linkage between the event and the repair. Initial data required by the form are fault classification and a description of the failure event, if shutdown is due to failure.

Table 4 and Fig. 3 request the constituents of downtime and the primary parameter of interest to the maintainability engineer. Downtime is the time interval between incipient shutdown and the return to normal operating conditions. The general objective of the maintenance engineer is to reduce the downtime to as short a time as is possible within the constraints of other considerations (i.e., safety, costs, etc.). The contributing elements to total downtime must be known to identify the contributors that have the best possibility of being reduced.

The time interval between the start of failure and complete equipment shutdown (ready for fault correction) is defined as the detection time. The method of fault detection should be recorded.

The time when a fault is noted should be recorded immediately following the fault occurrence. Frequently, the increment of time is very small, especially when a performance monitor is at or near the location of the fault. On the other hand, if the fault detection method is by product testing and the fault occurred near the input to the system, the time interval between incipient failure and its detection may be significant.

Detecting a fault does not always identify the location and cause of the failure. Consequently, diagnosis of the failure and deciding the appropriate corrective action can be time-consuming. Thus, the time interval between complete system shutdown and the beginning of actual physical fault correction is defined as the diagnosis. The method of fault diagnosis and unsuccessful attempts to diagnose the fault should be recorded.

Correction time is the time interval required to physically correct the fault. It includes the preparation time to perform the repair, the time to study the repair procedures and technical manuals and data, the time to collect special tools and replacement parts, and the time to acquire special skills through practice. The time to physically correct the fault is another component of correction time. Frequently, this time interval is incorrectly defined as the system downtime.

Once the repair is complete, it must be verified that the fault has been corrected. Although this is often a simple matter and can be done by the repairman rapidly, it may be time-consuming. Additionally, if the diagnosis was incorrect, the whole process of fault correction may have to be repeated.

Often substantial time is spent on administrative functions related to fault corrections. For example, management must be notified of a failure event, and the appropriate report forms must be completed. Once the fault is corrected, approval for restart may be needed from quality assurance, quality control, licensing groups, etc. Every effort should be made to minimize downtime from these causes, within prudent limits.

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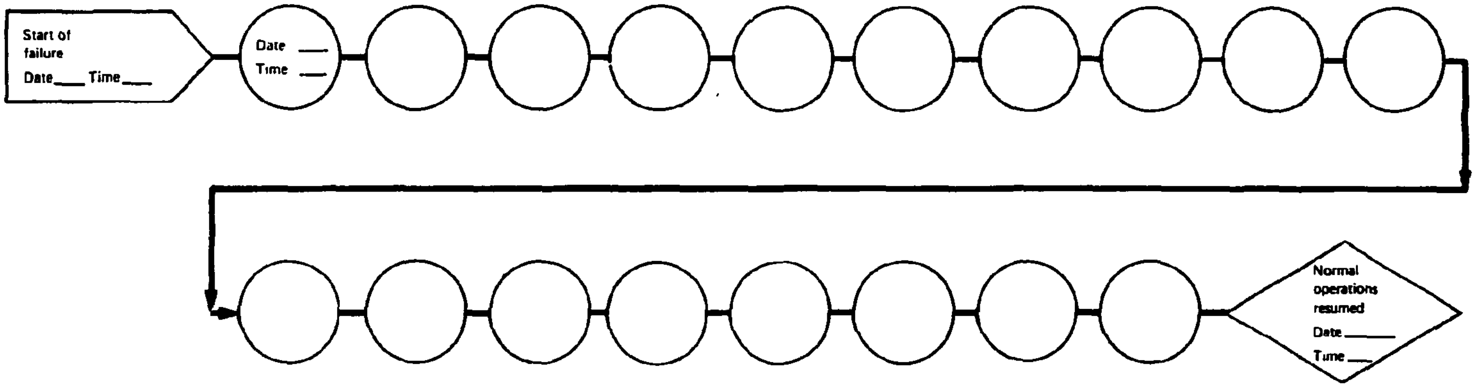

Instructions for drawing time-line:

The circles should contain the following information:
(1) activity number identifier from Table 1,
(2) date of that activity, and
(3) time started. All circles need not be used.

Fig. 3. Critical path time-line.

Table 4. Maintainability data for prototypic equipment

1. Installation	5. Report No.
2. System	6. Date of event
3. Item description	7. Time of event
4. Event description	8. Item inventory No.

9. Fault classification if shutdown is due to a failure
   - ☐ Break-in
   - ☐ Design fault
   - ☐ Random
   - ☐ End of design life

10. Description of failure, if shutdown is due to a failure
    - a. What was the defective item?
    - b. How was the fault detected?
    - c. What was the method of diagnosis?
    - d. Briefly describe diagnosis

Distribution of downtime

1. Complete time-line

2. From Fig. 3, what is the following?

   a. Total critical path downtime interval

   b. Active repair/maintenance time interval
      1. Detection time interval
      2. Diagnosis time interval
      3. Correction time interval
      4. Verification time interval

   c. Administrative time interval

   d. Logistics delay time interval

Table 4 (continued)

Legend for time-line

1. Active repair time
    - a. Detection time
        1. Estimated time failure started
        2. Fault detected
        3. Shutdown initiated
        4. Shutdown complete
    - b. Diagnosis time
    - c. Correction time
        1. Component isolation
        2. Access to faulty part achieved
        3. Decontamination
        4. Component removed
        5. Repair sequences completed
        6. Component replaced
    - d. Verification time
        1. Checkout (including calibration, alignment, deisolation, etc.)
        2. Normal operations resumed
2. Administrative time
    - a. Processing
    - b. Administrative verification (QA, safety regulatory, etc.)
    - c. No activity on this item, available work force concentrated on higher priority jobs
    - d. Administrative delay
3. Logistics delay time
    - a. Supervisor/crew travel
    - b. Replacement part reorder
    - c. Preparation time
        1. gather materials and technical data
        2. gather equipment, special tools and instruments
        3. study correction procedures
        4. practice on prototype

The number of shifts each day the facility is manned falls within the administrative downtime category. Clearly, the total clocktime, that is, the time interval between incipient failure and return to normal operations, should not be charged if the facility is manned for 8 h of a 24-h day.

There may be other sources of downtime not explicitly stated in Table 4. If some element of downtime becomes a significant contributor to the total downtime, it should be identified. For example, if approval from licensing authorities is preventing restart and becomes a significant contributor to downtime, it should be stated explicitly. Still another example might be insufficient feed input to the system or facility.

The above list of time increments are the constituents of total downtime. It is recognized that some elements of downtime may proceed in parallel or overlap with other elements so that the sum of these time intervals might be greater than the total downtime. It is necessary to resolve these into a critical path time-line. Figure 3 helps to visualize this through the use of a critical path time-line schematic. Although administrative functions are conducted throughout the failure event, they become critical path elements in only a few instances in this illustration. The total downtime is the duration of the critical path time-line.

Maintenance plans, concepts, and preparation are as important as equipment system design in achieving short downtimes. Typical key questions might be: Is the approach to an anticipated fault correction appropriate? Is there adequate preparation? Is the repair procedure well defined beforehand? Table 5 lists key elements of maintenance policy that should be recorded from each maintenance experience.

The frequency of failure events can be reduced by preventive maintenance programs. The deterioration of equipment must occur in some predictable fashion to justify taking preventive maintenance action. For example, the wear a mechanical part experiences can be monitored, and, presumably, the part can be replaced before the wear exceeds tolerance limits and the system product falls outside specification limits. Failure distribution functions (number of failures vs time) from reliability analyses are of great assistance in establishing a schedule for preventive maintenance. Preventive maintenance practices are not useful, and even contribute to downtime, if failures cannot be predicted or modeled. Random failures will always occur and this must be accepted.

The repair location for the failed item influences the approach and cost of the fault corrections. Generally, it is faster and less costly to repair or replace the item in situ rather than to remove the item to a maintenance area, repair it, then reinstall it in the failed equipment. Repairing the device onsite is generally quicker and cheaper than returning it to the manufacturer for repair. Often it is quicker and therefore less expensive to remove the failed item and replace it with a spare. The failed item can then be repaired at a more leisurely pace while the system is operating.

The replacement approach to a fault repair leads to some logistic considerations. An inventory of spare parts must be kept on hand and warehoused. If a desired spare part is not on hand, an emergency order must be placed for it. The time to order and receive the part might become time limiting in this circumstance. Thus, added to the logistics of fault correction, are the logistics of warehousing and cataloging the inventory of needed special tools, monitoring instruments, and safety equipment.

Table 5. Policy

1. Reference the pertinent procedures and technical manuals.

2. Preventive maintenance:
   a. What is the preventive maintenance frequency?
   b. Identify possible preventive maintenance tasks resulting from this event.

3. Fault correction policy
   a. This event:
      1. Disposition of failed item:
         ☐ repair ☐ replace with spare, repair item ☐ replace with spare, discard
      2. Repair location:
         ☐ in-place ☐ lab bench, hot cell ☐ lab bench, cold cell ☐ factory

4. Technical data, manuals:[a,b]

a. Manuals were clearly and accurately written.	Yes	1	2	3	4	5	No
b. Procedures planned for the event were adequate.	Yes	1	2	3	4	5	No
c. Tasks were logically sequenced.	Yes	1	2	3	4	5	No

5. Logistics

a. Manuals listed all required special tools and facilities.	Yes	1	2	3	4	5	No
b. Manuals listed all required special monitoring and calibration instruments.	Yes	1	2	3	4	5	No
c. Manuals identified necessary safety equipment.	Yes	1	2	3	4	5	No
d. There was an adequate inventory of spare parts and consumables.	Yes	1	2	3	4	5	No

---

[a] Score categories 4 and 5 according to one of the following statements: (1) feature was clearly present, (2) feature was reflected to a great extent, (3) feature was not applicable, (4) feature was reflected to a small extent, or (5) feature was clearly not present.

[b] If not available, describe in detail.

Table 5 (continued)

e. Emergency reorder for parts was minimized. Yes __ __ __ __ __ No
1 2 3 4 5

6. Comments on policy

A mature, well-tested equipment system will have documented data and repair procedure manuals. The maintenance manual in particular is a "living" document that should be routinely updated as the body of maintenance experiences accumulate.

Table 6, Feedback of maintenance experience to design decisions, requests operational and test data which will relate the design of the equipment system to maintenance activities. The table is a checklist of broad generic categories related to design decision. The design features given in Table 6 are self-explanatory and need not be discussed further.

The bottom-line conclusion of a maintenance experience is whether the maintenance concept, philosophy, or approach is appropriate for a particular fault correction. Equipment that processes radioactive material can serve as an example of various maintenance concepts. For example, if an equipment fault occurs (1) the repair may be done by personnel in direct contact with the equipment, but with the penalty of being exposed to some degree of radiation; (2) the equipment may be decontaminated and contact repair performed; or (3) the complete repair may be done remotely. The variety of data collected and recorded as outlined in this and previous sections can help provide the basis for sound judgment regarding the effectiveness and appropriateness of particular maintenance philosophies.

A pervasive characteristic of maintenance activities is that people interact with machines to return them to normal operating conditions. This adds a new dimension to evaluations directed at shortening downtime. The capabilities of repair personnel must be defined, and the equipment must be designed to facilitate repair. Table 7, Human factors and personnel, lists the categories and number of personnel required for each event, technician skill levels, and selection requirements. Additionally, information is requested concerning key features of machine design that directly impact the human factor, that is, equipment part labeling and coding, the possibilities of incorrect connection and assembly, ease of handling parts, awkward or tedious job elements, etc.

7. DATA COLLECTION, STORAGE, RETRIEVAL, AND ANALYSIS

7.1 Data Collection

Large amounts of data are required for a complete availability analysis. Test operators and technicians may resist the responsibility of collecting additional information because of a lack of understanding of the value of reliability and maintainability data and because the large amounts of data add to their workload. Methods must be devised that address this problem and facilitate data collection.

A "tag method" can alleviate the problems of copious data collection. In this approach the technician or equipment operator places a tag on problem equipment parts, writing only brief information (i.e., the time and date, the malfunction sympton, and apparent fault) and then signing the tag. Later, a person with the designated responsibility of collecting the RAM data interviews the engineers, operators, and technicians and completes the longer data forms.

The tag method for equipment fault data collection offers a number of advantages over having the equipment operators and technicians complete the forms. It removes the burden of collecting and interpreting data from the test operators and technicians. The one individual who collects the data can be better trained in the preliminary interpretation

Table 6. Feedback of maintenance experience to design decisions[a]

1. Is the maintenance concept (remote vs contact) compatible with the design?

   ☐ yes ☐ no

2. What were the distances to adjacent equipment from direction of access (inches)?

   _____top _____bottom _____right side _____left side

3. What should be the minimum separation distance?

4. Complexity of task:

   a. Adequate accessibility, work space clearances to failed parts, test points, adjustments, and calibrations Yes __ __ __ __ __ No
   1 2 3 4 5

   b. Modularized components and parts Yes __ __ __ __ __ No
   1 2 3 4 5

   c. Number and variety of tool accessories and support equipment were as low as practical Yes __ __ __ __ __ No
   1 2 3 4 5

5. Need for and frequency of design dictated maintenance:

   a. Preventive maintenance requirements were as low as practical Yes __ __ __ __ __ No
   1 2 3 4 5

   b. Fail-safe features were incorporated Yes __ __ __ __ __ No
   1 2 3 4 5

   c. Tolerances were designed into equipment that allowed for use and wear throughout life Yes __ __ __ __ __ No
   1 2 3 4 5

   d. Adequate corrosion prevention and control features Yes __ __ __ __ __ No
   1 2 3 4 5

6. Maintenance downtime:

   a. Rapid and positive detection of the malfunction Yes __ __ __ __ __ No
   1 2 3 4 5

---

[a] Score categories 4 through 7 according to one of the following statements: (1) feature was clearly present, (2) feature was reflected to a great extent, (3) feature was not applicable, (4) feature was reflected to a small extent, or (5) feature was clearly not present.

Table 6 (continued)

b. Rapid and complete preparation to begin maintenance — Yes ___ ___ ___ ___ ___ No
1 2 3 4 5

c. The level of repair corresponded to the planned level of skills, space, and test equipment — Yes ___ ___ ___ ___ ___ No
1 2 3 4 5

d. Easy fault correction — Yes ___ ___ ___ ___ ___ No
1 2 3 4 5

e. Rapid and positive adjustments and calibrations — Yes ___ ___ ___ ___ ___ No
1 2 3 4 5

f. Rapid and positive verification of the correction — Yes ___ ___ ___ ___ ___ No
1 2 3 4 5

7. Design dictated support costs:

a. Specialized maintenance tools, support equipment, and facilities were as few as practical — Yes ___ ___ ___ ___ ___ No
1 2 3 4 5

b. Depot or factor maintenance was minimized — Yes ___ ___ ___ ___ ___ No
1 2 3 4 5

c. Required maintenance technical data was minimized — Yes ___ ___ ___ ___ ___ No
1 2 3 4 5

8. Comments on design:

Table 7. Human factors and personnel[a]

1. Estimated number of personnel	Quantity	Man-hours
Technicians	___	___
Engineers	___	___
Management	___	___

2. Possibility of confusion in labeling, coding, technical data, or part identification
low ___ ___ ___ ___ ___ high
1 2 3 4 5

3. Possibility of incorrect connection, assembly, installation
low ___ ___ ___ ___ ___ high
1 2 3 4 5

4. Physical demands (e.g., lifting heavy weights) on personnel
low ___ ___ ___ ___ ___ high
1 2 3 4 5

5. Number of dirty, awkward, tedious, or fatiguing job elements
low ___ ___ ___ ___ ___ high
1 2 3 4 5

6. Ease of handling, mobility, transportability, and storability
low ___ ___ ___ ___ ___ high
1 2 3 4 5

7. Recommended skill level of maintenance personnel for this event in a production facility
   a. Task analysis low ___ ___ ___ ___ ___ high
   b. Knowledge of procedures low ___ ___ ___ ___ ___ high
   c. Knowledge of equipment low ___ ___ ___ ___ ___ high
   d. Need for practice on prototype low ___ ___ ___ ___ ___ high
   e. Overall skill level requirements low ___ ___ ___ ___ ___ high

8. Recommended level of technician selection for this event in a production facility
   a. Education low ___ ___ ___ ___ ___ high
   b. Experience low ___ ___ ___ ___ ___ high

---

[a] Score categories 4 through 7 according to one of the following statements: (1) feature was clearly present, (2) feature was reflected to a great extent, (3) feature was not applicable, (4) feature was reflected to a small extent, or (5) feature was clearly not present.

Table 7 (continued)

c. Aptitude low ___ ___ ___ ___ ___ high

d. Motivation low ___ ___ ___ ___ ___ high

e. Physical attributes low ___ ___ ___ ___ ___ high

1. lifting capability low ___ ___ ___ ___ ___ high

2. dexterity low ___ ___ ___ ___ ___ high

9. Comments on human factors and personnel:

of the data. This person will learn rapidly what information to seek; consequently, the data will be of higher and more consistent quality.

Data are collected in maintenance demonstration runs in the CFRP by analysis of video tapes. Maintenance experiments to confirm a designed repair capability and to measure alternative maintenance concepts are video taped. This procedure provides a permanent record of the active repair and enables reanalysis as knowledge is gained and information is updated.

Constituents of downtime, other than active repair time, can also be obtained from operational reports and log books. Although elaborate recordkeeping (such as video tapes) enhances the depth of information obtainable, it is not a substitute for written reports and log books provided by engineers, operators, and technicians.

7.2 Data Storage, Retrieval, and Analysis

A specialized computer information system should be established for large-scale reliability and maintainability test programs. Data and information provided by the special forms previously described are recorded in a format acceptable to standard codes, such as SAS[10-12] (SAS is the registered trademark of SAS Institute, Inc., Cary, North Carolina). An example of such an information system is described in Ref. 13. The data are permanently stored on computer disk. At ORNL, access to data sets is accomplished through a question/answer interactive procedure that assists the user in identifying specific portions of the information required for any given assessment.

The SAS approach offers a variety of options for manipulation and analysis of the data base: it can create charts, tables, estimates of means, t-tests, or analysis of variance. Several chart options are available, that is, vertical and horizontal bar charts, 3-D block charts, and pie and start charts. The SAS charting procedure can be used to generate simple or complex graphs. Graphs may range from linear plots to drawing and shading of contours, or superimposing two or more plots. A simple linear plot of RAM data might be corrective repair time vs equipment complexity.

Frequency distributions of variables are often useful and can easily be obtained using the SAS system. Frequency and cross tabulation tables may be generated, as well as several measures of association (deviation from expected values, contingency coefficients, chi-square tests of independence, etc.). The software package can estimate much more than the mean of a distribution. By listing various options, the user may also evaluate the coefficient of variation, skewness, t-test, sums of several variables, etc.

In summary, through the use of existing computer software packages, data storage allows immediate analysis, that is, when the data is stored in a format acceptable to a standard statistical analysis system such as SAS, existing computer software packages can be immediately applied to the data set. This procedure vastly accelerates the retrieval and interpretation of data.

The interaction of a data set, in which information is continually being added, offers several advantages over storing information only in written reports. Reports often summarize the raw data but do not always present comprehensive conclusions. The raw data are frequently lost or destroyed. It is impossible to forecast the analyses, requirements, or topics that may be of future interest. Experiments can be reanalyzed at some future date if there is easy access to all of the raw data. Otherwise, the tests may have to be repeated.

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