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Reliability Engineering in Solar Energy: Workshop Summary

Gordon Gross

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A Division of Midwest Research Institute

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PREFACE

This document presents an overview of the contents of the 30-31 May 1979 workshop on "Reliability Engineering in Solar Energy Conversion" that was held in Denver, Colorado, by the Solar Energy Research Institute (SERI). The report also discusses the need for a reliability program in all solar efforts and suggests initial actions toward this goal. The paper results from efforts of many persons who planned and prepared the program, presented discussions, and led workshop sessions. Most of the speakers are acknowledged in the report.

Two speakers, otherwise unidentified in the report, deserve special credit for their contributions. They are Professor Alvin S. Weinstein of Carnegie-Mellon University and Dr. Safron Canja of the U.S. Department of Energy (DOE). Professor Weinstein's lecture on product liability dramatically showed the need for our concern about the durability and safety of products and designs. Dr. Canja presented an excellent review of the DOE fossil energy reliability program that can eventually serve as a model for solar energy reliability.

The chairman of the workshop and editor of the report accepts responsibility for his possible shortcomings and gratefully acknowledges the assistance of all participants. Particular appreciation is extended to the editorial committee that includes W. F. Carroll, Jet Propulsion Laboratory (JPL); H. A. Lauffenburger, SERI; Dr. R. Ross, JPL; E. Royal, JPL; E. Waite, Argonne National Laboratory (ANL)-West; and R. M. Wolosewicz, ANL.

This report was part of Program Area 16 (Quality Assurance and Standards) of the SERI FY79 Program, directed by the Quality Assurance and Standards Branch of the Technology Commercialization Division. The Materials Branch of the Research Division of SERI provided materials and engineering support.

Approved for:

SOLAR ENERGY RESEARCH INSTITUTE

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SUMMARY

A workshop was held to review the present level of reliability-related efforts in solar and nonsolar technologies and to develop suggestions for ways to establish a unified program for such efforts throughout the evolving solar energy conversion field. The extent of treatment of the matters of reliability, durability, maintainability, and safety (RDM&S) by the military, electric utility, refrigeration, and telephone establishments was reviewed by experts in those areas. The solar energy conversion fields of heating and cooling, photovoltaics, biomass, wind, and solar thermal electric generation were also reviewed. This report contains condensations of the discussion on each of the areas covered.

The goals of this report are the stimulation of interest in RDM&S as a recognized need in all solar development and demonstration projects, the establishment of a "community of interest" among those involved in RDM&S aspects of such projects, and the eventual development of a unified program of RDM&S activities in all such projects.

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SECTION 1.0

INTRODUCTION

This report covers a workshop entitled "Reliability Engineering in Solar Energy Conversion," which was held in Denver, Colorado on 30-31 May 1979 and discusses a broad reliability program for solar projects. The meeting was arranged by SERI, but most of the credit for its content must go to the speakers and workshop leaders listed in Appendix C. Objectives of the workshop and of subsequent related efforts are to initiate communications between the reliability, durability, maintainability, and safety (RDM&S) activities of the various solar energy sectors and to establish a community of interest in these endeavors.

No formal papers are included as in a conference proceeding. The report, instead, presents perspectives on the importance of RDM&S in nonsolar and solar technologies and encourages attention to RDM&S in all solar energy tests and demonstrations. From this report goal, one must not infer a lack of concern about reliability in DOE's solar R&D. There are solar RDM&S programs as thorough as those that can be found in any technology.

To be effective, a RDM&S program must be designed for the specific needs of a component, subsystem, or system. RDM&S programs for solar energy will eventually be similar to programs for commercial products in which the consequences of degradation/failure are economic and include operational cost of service outage and replacement. Although commercial RDM&S programs are based on the same principles that are used in space, military, and nuclear applications, they require grossly different implementation. In order for projects to benefit each other in this embryonic stage of development, solar RDM&S programs may need to be more elaborate than the commercial programs they will later resemble.

Persons outside the professional areas of reliability, quality assurance, and related fields tend not to recognize the differences in these areas. For the purposes of this report, the following terms will be used.

- Reliability - the probability that a component or a system will perform its required function under specified conditions for a specified time.
- Availability - the probability that a system will be operational at a given time under specified conditions (not directly addressed in this report).
- Durability - the ability of a system, subsystem, component, or material to resist the effects of environment, handling, installation, and use.
- Maintainability - the probability that a failed system or component will be restored to an operable condition within a specified period of time when the maintenance action is initiated under stated conditions.
- Safety - the ability of a system, subsystem, component, or material to limit or avoid harm to persons or property during any operation or failure.
- Quality assurance - the set of practices and methods whereby systems, subsystems, components, and materials can be selected for their ability to meet or exceed standards indicating acceptable degrees of reliability, durability, maintainability, safety, or performance (not directly addressed in this report).

RDM&S are of great concern in solar energy conversion because they strongly affect the rate of entry of solar technologies into the commercial sector. Consumer acceptance is influenced by the negative publicity that accompanies any failure in a solar installation. Acceptance by large users, such as electric utility companies, depends on the certainty with which they can expect to serve customers through a particular technology. All potential users are influenced by the initial and life-cycle cost of solar applications, and these costs are inexorably related to RDM&S.

The achievement of high reliability requires carefully planned efforts beginning with early design and continuing throughout a system's life cycle. Methodologies have evolved from experience in other technical fields and system applications that, perhaps, can be drawn upon in developing a program for solar-energy conversion applications. The workshop tried to understand practices employed in nonsolar sectors and in several current solar energy conversion programs.

The immediate needs of RDM&S are for obtaining, processing, and disseminating appropriate data. Projects must also foster the sharing of ideas, methods, and results because data are needed by those who evaluate choices in solar applications - designers, builders, users, and providers of capital. Numerous past experiments or field demonstrations of solar hardware have not collected information related to RDM&S. This omission has permitted repetition of faults in design, material selection, manufacture, and installation. The workshop aspired to identify practices that would assure the availability of information to prevent such duplication of faults. This information can lead to improved designs, lower life-cycle costs, and greater confidence in solar energy technologies.

It is hoped that this report will lead toward a unified reliability program bridging all DOE solar endeavors. A workshop on reliability of photovoltaic systems is reported to be in the preliminary planning stage to be held in 1980. SERI is managing a program to develop performance criteria and test standards for photovoltaic systems and components.

SECTION 2.0

THE WORKSHOP

The first day of the workshop covered RDM&S in nonsolar areas and in solar projects. Group discussions to generate the first steps of what one hopes will become a unified program of solar RDM&S studies made up the second day.

This initial meeting identified a community of interest among solar energy experimenters and program personnel. It also encouraged many persons to cooperate in developing viable plans, which can be adapted to work schedules or future projects, to collect and manage RDM&S data.

Although the first courses of action will be revised repeatedly before a national solar RDM&S program, it is important that some plan of action be initiated.

2.1 RELIABILITY IN TECHNOLOGIES OTHER THAN SOLAR ENERGY CONVERSION

The first half-day session of the workshop presented the many ramifications of RDM&S as viewed by business, industry, and society. The speakers and the areas they represented are as follows:

- Dr. James H. Witt, ARINC Research Corporation
  A survey of performance assurance programs applied by government agencies.
- Dr. Randall W. Pack, Electric Power Research Institute
  Electric plant systems performance programs and utility system needs in reliability.
- Mr. Frank E. Kalivoda, Copeland Corporation
  Reliability and product evaluation in refrigeration machines.
- Mr. Bliss D. Jensen, Bell Telephone Labs
  Reliability programs in the communication industry.

For further identification of speakers see Appendix C. These discussions reflect the interest of consumer-directed industries and federal programs in RDM&S. Similar attention must be devoted to solar energy conversion if it is to become commercially viable.

Although not serving a consumer interest, the federal programs in RDM&S can guide the development of a solar energy reliability program. Most of these programs depend on acceptance standards and tests. NASA continuously reviews contractors' or suppliers' programs during acquisition to assure the quality needed to meet RDM&S goals. All keep formal records to track maintenance activities and most have specific failure analysis programs. The data supplied by these programs serve three purposes: (1) to identify weaknesses in systems to upgrade or redesign them; (2) to estimate the safety and availability of systems; and (3) to improve the accuracy in estimating life-cycle costs of the systems. Thus, the federal programs will be very useful in designing a solar energy RDM&S program.

One potential market for solar energy application is the electric utility industry. Constraints placed on that industry by public regulatory agencies, economy-of-scale effects, and institutional requirements such as environmental rules all lead to a need for large, extremely dependable (i.e., available) systems. The utility industry is often pressed to spend ten or twelve years putting on-line a system that may cost $1 billion and incur losses of $1 million per day when unavailable. This prospect causes the industry to demand knowledge of a system's availability as well as of the costs of maintaining it. As product liability attitudes develop along present lines, the industry must also become more interested in system safety. If solar energy conversion is to be "sold" to the electric utility industry, it is mandatory that reliability be optimized and its statistical measures be accurately known.

The solar heating and cooling of buildings and the heating of water for domestic uses will require consumer hardware that is similar to other home appliances. The refrigeration compressor industry serves as a model for a reliability program for major appliance components. The reliability program in one well known company in this industry is supported by top corporate management and is committed throughout its structure to producing a reliable product.

Testing, failure mode analysis, and data collection are central to the reliability program in the refrigeration compressor industry. Large banks of compressor test stations are used to test duplicates of a refrigeration compressor under normal and extreme conditions. Although impractical in these early days of solar hardware manufacture because of low production rates, such duplicative tests must become routine for component reliability programs before consumer confidence will develop. Failure mode analysis is not so dependent on the availability of many samples and can thus be applied from the beginning in solar energy system development. The reporting of causes and effects of failures will greatly accelerate reliability in solar hardware. The present lack of regular failure analyses in solar hardware permits the repetition of faulty design and installation practices as well as erroneous choices of materials.

The telephone industry presents a unique collection of a price competitive, technically advanced field that deals with a widely used, nearly commonplace consumer product. The technology of modern telephones, particularly those in a business communication system, is similar to that of computers. The complexity of the system is great, the demand for reliability is high, and the competitive pressure requires low costs. In the telephone industry, extensive quality assurance activities occur at the manufacturing level. Maintenance and reliability data, however, are usually collected in the field and the practices here can be a useful guide to a solar energy RDM&S program. A leading telephone system company applied human engineering to design methods for gathering field data to maximize the number of service reports submitted by field personnel. Even the size and shape of the report forms are designed to avoid inconvenience to the serviceperson. The methods employed by industries and government will be used in the program suggestions, which follow later in this report.

2.2 RDM&S PLANS AND ACTIVITIES IN THE SOLAR FIELD

The second half-day session encompassed activities in several areas of solar energy conversion. The speakers and their fields in this session were:

- Dr. Prem Chopra, Argonne National Laboratory
  The Active Heating and Cooling Program

- Mr. Ed Royal, Jet Propulsion Laboratory
  The Photovoltaics Program
- Dr. Ralph Wentworth, Dynatech, Inc.
  The Biomass Fuels Program
- Mr. Robert Lynette, Boeing Engineering and Construction
  The MOD-2 Wind Turbine System
- Mr. Harvey Golding, McDonnell Douglas A.C. Co.
  The 10-MW solar thermal electric plant at Barstow, California.

Appendix C further identifies these speakers.

Each solar program has a different approach to RDM&S. The most extensive treatment is given to the two largest systems, Wind MOD-2 and the 10-MW solar electric plant, because they are economically significant and are directed by organizations that originated many RDM&S practices. Perhaps RDM&S is least emphasized in biomass because that area is such a logical extension of the chemical process industry that much of the RDM&S activities needed are assumed without fanfare. The photovoltaics program, particularly the Low-Cost Solar Array program, has developed a complete RDM&S activity including field testing and failure analysis. The heating and cooling reliability and maintenance program has already produced data management software and has begun to refine a failure information data bank on both commercial and residential solar heating and cooling.

The hastening of these solar programs toward full-scale RDM&S activity encourages the development of a unified solar RDM&S program. The undertaking of such significant first steps shows that collection of useful RDM&S data is feasible in solar experiments. This report will suggest initial stages of a complete program that should be expanded as government policies, funds, and technical development permit.

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SECTION 3.0

THE SOLAR ENERGY RDM&S PROGRAM

On the basis of thoughts developed in the workshop, we will consider in this section the needs of RDM&S programs and brief recommendations that might serve as a start toward the objectives of the workshop.

Stressed by most workshop participants, the preventative approach to program assurance recognizes that management of system reliability must be initiated during its design concept and must be extended throughout its life cycle. A well-designed program will encompass a wide range of tasks covering testing, assembly process control, maintenance and repair procedures, failure reporting, and corrective action control. Figure 3-1 illustrates the relationship between the common product assurance control tasks during the design-to-retirement cycle of a product.

Although the methodology applies to any control program, effective implementation of a program for a particular product or market requires judicious adaptation. The choices are dictated by application criticality, consequences of system malfunction, degree of customer procurement control, competitiveness of market, warranty costs, organization structure, operating policies, etc. Control programs applied to the procurement of space systems are extremely sophisticated as are those for nuclear power generating systems. In both applications, mission failures may have very grave consequences, and system procurement is rigidly controlled by the consumer or regulatory agency. Great emphasis is placed on compliance with regulations through extensive testing at the component, equipment, and system levels. At the opposite extreme, manufacturers of many consumer products may have a much more loosely organized program, although the advent of Occupational Safety and Health Administration, of Consumer Product Safety Commission, and of consumer protection regulations have resulted in significant changes in attitude over the last few years. Because of warranty cost and liability suits, manufacturing organizations are adopting more formal quality assurance programs such as the one pursued by a manufacturer of refrigeration compressors as discussed at the workshop.

RDM&S programs adopted for solar energy systems should resemble those of the commercial sector. The market will probably be quite competitive and, except for codes and regulations imposed by governments, the customer is expected to exercise nominal control over the procurement. In this scenario, the RDM&S programs that evolve will stress design practices, process controls, in-process inspections, field data feedback, and warranty considerations. Laboratory tests would be performed primarily as an engineering development tool; field testing and in-service experience would provide feedback to the design process.

The development of prototype RDM&S programs for solar energy system hardware should be a long-range objective. Because such programs affect product development and integrity, life-cycle costs, and customer acceptance, they must be designed with great care. One might begin with an in-depth study of the quality assurance programs employed in the conventional power generating industry.

Accessibility to factual engineering data and information is essential to the success of any RDM&S program. Analyses and decisions must be based on information derived from laboratory tests and field experience relative to quality defects, material degradation, failure rates, failure mechanisms, environmental susceptibility, etc. Because this type of

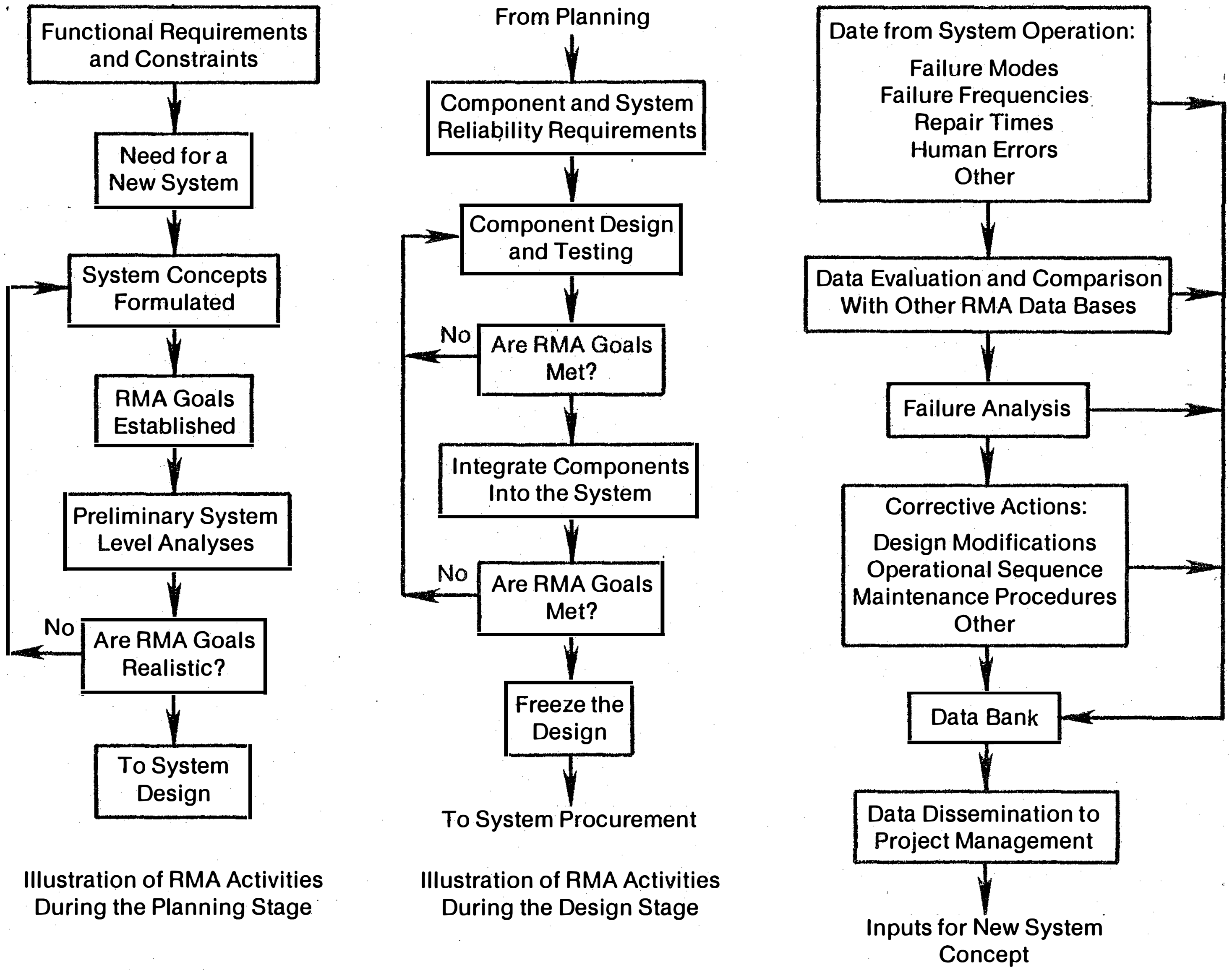

Figure 3-1. Product Assurance Control Tasks in Design-to-Retirement Cycle of a Product.

data is now sparse for materials, components, and subsystems used in solar energy conversion, one needs urgently to establish a data feedback that will collect, compile, and analyze all data being generated on solar energy research, development, test, and demonstration programs, and that will disseminate data to key users. Such data can be useful only if the component or item reported on is clearly identified and the quality being reported is well defined.

Toward the acquisition, classification, reduction, and analysis of RDM&S data and its synthesis into useful engineering information, one must precisely identify the information needs of the end users and interpret them into supportable data system products.

The quality of input data must be assured when a data system is designed. Because the data feedback system endeavors to provide access to all prior experience, it must assure the integrity of the information it disseminates. Because the system usually only minimally influences the conduct of the experiments, it must establish rigid acceptance criteria for data offered for input. Data must contain documentation describing the experiment objective, characteristics of the items being evaluated, applied stress, environment and load conditions, failure definition, etc. The evaluation should be conducted against an accepted procedure, and the submission should contain an authorizing signature. For maximum assurance of validity, an engineering judgement should be made of results before acceptance to ascertain whether results are consistent with those of similar experiments. One cannot overemphasize that to attain acceptance of the data feedback system, user orientation must pervade all decisions relative to the design and operation of the system.

In an emerging technology, knowledge of material, component, and system failures is of great importance to researchers and engineers who establish priorities on research studies and product improvement efforts. A problem with rapidly advancing technologies is the lack of accepted practices and techniques for identification of faults, analysis of failures, and isolation of failure mechanisms. Frequently, failures are not examined at all. Thus, much badly needed information is lost. The following solutions are available:

(1) Develop a uniform reporting protocol for all observed malfunctions.

(2) Develop guidelines for conducting failure autopsies and develop standard proce dures for key areas.

(3) Establish methods for promoting and coordinating the failure autopsy activities and reporting results.

(4) Assign responsibility for failure autopsies to agencies specializing in the relevant technologies.

Although many feel that a central facility for all failure analysis and reporting would assure most consistent results, that plan has severe disadvantages. The cost of instrumenting and staffing such a laboratory to accommodate the variety of necessary technologies, materials, and devices would be prohibitive. Also, one can question the ability of an organization of manageable size and funding to remain competent with all technological advances.

In stabilized, mature industries, the second solution is commonly practiced. The interchange of information and techniques is partially formalized but much communication remains as informal dialogue between failure analysis practitioners.

The solution that now seems most advisable for solar energy combines the features of the third and fourth solutions. A protocol should be developed to provide a basis for investigating each malfunction in sufficient depth to ascertain why and how it failed. A single agency, associated with each major program office (e.g., photovoltaics, biomass, and solarthermal) should assure the analysis and reporting of all failures. With this approach, failure analysis studies would be conducted by those laboratories having the necessary resources and expertise as part of their normal functions.

In summary, the development of solar energy systems that can successfully compete with other forms of energy in the marketplace is contingent upon the research, development, and production of cost-effective systems. This report recommends the development of programs aimed at providing decision makers and practitioners with disciplines, tools, information, and guidance that will help accelerate the process. Further considerations of a possible RDM&S program begin in Section 3.1. Recommendations for establishing a data feedback mechanism as a first step in this program are presented in Section 4.0.

Examples of RDM&S programs in solar technologies, including the details of data gathering, evaluation, and reporting, and of interactions between field engineers and operators are presented in Appendices A and B.

3.1 FIRST STEPS OF THE RDM&S PROGRAM

3.1.1 Maintenance Records

The maintenance staff on a project has the greatest opportunity to observe weaknesses in a system and to report information about them. Therefore, maintenance activities should be used as a data source. A maintenance log should be kept with entries for all maintenance operations, which fall into two categories:

- Regularly scheduled maintenance, and
- Unscheduled maintenance.

Regularly scheduled maintenance includes those operations performed regularly for optimum system performance and include calibrations, corrosion treatments, cleansing, lubrications, etc. Possibly the most important reason for keeping records of such data is to evaluate the effectiveness of the maintenance program. This documentation also provides information about the performance of the equipment.

The unscheduled maintenance information provides the bulk of random failure data for the program. This information comes from the trouble calls resulting from unexpected problems that uncover information not only relevant to random failures, but also to environmental conditions, design completeness, and manufacturing adequacy.

3.1.2 Suggested Minimal Logging and Reporting Format

The production of useful data from the maintenance log requires that reports be regularly made. All demonstration and experimental projects should provide a monthly RDM&S report that includes all of the maintenance effort performed during the past month. The report should indicate if no maintenance effort was required during the reporting period.

The production of useful data from the maintenance log and report requires that at least the following items be provided:

- Identification
  - Project identification
  - Component type (i.e., pump, valve, control valve, etc.)
  - A unique functional identification number
  - A unique component identification such as a serial number
  - Component manufacturer identification
  - Model number

- Description of maintenance effort
  - Date of maintenance
  - Indication of scheduled or unscheduled effort
  - Mode of failure
  - Probable cause of failure
  - Component installation date
  - Estimated operating time since last maintenance call for item
  - Comments about the level of maintenance required for this specific component and function, accessibility of the component for ease of maintenance, availability of spare parts, replacement items, etc.
  - Name of person and firm performing work
  - Cost or time and parts required for the maintenance call

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SECTION 4.0

RECOMMENDATIONS FOR RDM&S ACTIVITIES

Before delving into recommendations for RDM&S activities, one must recognize that many major DOE solar energy conversion programs already contain excellent RDM&S tasks. This report section is written with the hope that the methods suggested by those efforts can be adapted to all DOE-supported solar programs.

Two basic issues that should shape an RDM&S program are:

- The need within each solar technology for feedback of information from the field to the designers and manufacturers requires a closed-loop RDM&S program; i.e., design to production to field to design.
- The necessity for communication between solar technology sectors to allow use of those RDM&S data that may be applicable outside the technology in which they were developed:
  - Requires development of methodologies for gathering, analyzing, and handling data to assure its quality;
  - Requires procedures to facilitate use of data from specific technology centers by persons from other technologies;
  - Requires centralized data banking in addition to that practiced at specific technology centers to assure uniform access;
  - Requires regular communication including frequent (e.g., semiannual) meetings providing a professional exchange of ideas among persons involved in RDM&S aspects of solar energy; and
  - Would benefit from annual project summaries, overall annual review, and informal monthly sharing of information by newsletter.

Basic RDM&S program design and management must originate in the specific centers performing lead work for each solar energy conversion technology. At the same time, the need for a uniform comparison of information across technological boundaries requires centralized data storage and retrieval facilities and a centralizing organization to facilitate communication. Software should be developed, for example, to identify patterns of failure in components or materials that might be common to two or more technologies.

Data handling should be tailored for each technical activity. It must be applied initially at very low levels in those projects that contained no task assignment or funding for RDM&S.

This section will not provide a complete RDM&S requirement: each project must develop its own RDM&S requirements. The information reporting specifications suggested here are flexible enough to accommodate the spectrum of disciplines contained within solar energy conversion. The following discussion suggests the first steps toward a RDM&S program.

Because field data from solar applications is most urgently needed in solar RDM&S, RDM&S programs must emphasize the gathering and reporting of such data—much of it from maintenance records.

Several solar projects have begun keeping daily maintenance records. It is essential that this practice extend to all solar projects in which components or systems are under test or use. Initially, no specific format will be applied; but it is the hope of those involved in the workshop committees that standardized coding and reporting practices can be developed for maintenance records. Guidance in that development will be sought from other RDM&S programs in the federal and commercial sectors.

More workshops must be held on RDM&S in Solar Energy Conversion to further develop a unified national program.

APPENDIX A

ARGONNE NATIONAL LABORATORY SOLAR RELIABILITY AND MATERIALS PROGRAM, DATA ACQUISITION ACTIVITY*

Field data from operational solar energy systems are required so that future systems can be designed to be more reliable and cost-effective. The Solar Reliability and Materials Program at Argonne National Laboratory (ANL) obtains data from the DOE-sponsored solar heating and cooling systems.

The ANL data acquisition interacts with the owners/operators of the solar system during start-up. Field data are evaluated and stored for later analysis in the ANL Solar Reliability and Materials Library. The following sections of this appendix discuss the ANL program's data acquisition.

A.1 RELIABILITY AND MAINTAINABILITY DATA REQUIREMENTS

Reliability and maintainability data requirements were established by examining reliability information from the electric power and the chemical industries, reviewing typical specifications for the design and operation of heating-ventilating and air conditioning systems and typical construction projects, and studying inputs from DOE-sponsored conferences and from the open literature.

The following data are used to evaluate reliability and maintainability of existing solar sites and to provide a data bank of operating experience:

- Descriptions of as-built systems
- Equipment specifications
- Operating mode description
- Flow schematics
- Sensor type and location
- Installation problems
- System checkout problems
- Operational performance
- Maintenance experience.

A.1.1 Data Acquisition

Site-specific technical data and operational information are acquired by using all communication channels between DOE and its contractors such as International Business

*See end of this appendix for references that will give further details of solar energy reliability/maintainability activities at Argonne National Laboratory.

Machines (IBM) and PRC Energy Analysis Company. A field engineering staff has been assigned to monitor the DOE-sponsored heating and cooling systems. These field engineers coordinate their site visits with the appropriate DOE contracting officer's representative (COR) and project managers (PM) at the following offices:

- DOE Chicago Operations
- DOE San Francisco Operations
- Marshall Space Flight Center
- PRC Energy Analysis Company.

Other data sources such as DOE sponsored conferences, various government publications, and component manufacturer specifications are being monitored and reviewed by the field engineering staff. These data are abstracted, filed in the Solar Reliability & Materials Library, and used for site evaluations.

The ANL field engineer assigned to monitor several demonstration sites reviews site background information, including design details provided by the proposals, system design descriptions, cost reports, monthly site status reports, and performance reports. This review aids in the preparation of a site-specific checklist for use during interviews with the COR/PM to obtain the site's history. A sample of one of the nine checklists is presented next.

A.1.1.1 Solar Energy System Checklist

1. Installation Problems
2. Absorber Plate
   - Selective Coating Problems
   - Leaks
   - Distortion
3. Cover Plates
   - Broken
   - Cracked
   - Coated (Inside/Outside)
4. Collector Seals
   - Separated
   - Deteriorated
5. Collector Frame
   - Corrosion
   - Structural Integrity

6. Collector Mounting to Roof
   - Any Leaks
   - How Attached
   - Expansion Provisions
7. Stagnation Protection
   - Heat Rejection
   - Other
8. Freeze Protection
   - What Type
9. Insulation
   - Temperature Stability
10. Roof Penetrations
    - How are they made
    - Any Problems
11. Other Site-Specific Items

A.1.2 Site Visits

To supplement the technical backgound information received from the COR/PM and IBM system analyst, the ANL field engineers inspect the operational solar energy systems. Before visiting a site, the assigned field engineers obtain the approval of COR/PM. The date of the visit is agreed upon by both the solar demonstration site contractor and the ANL field engineer. Field visits are planned so that at least two operational systems can be reviewed on each trip.

Field engineers take photographs to record equipment installation and location, as well as any subsystem or component failures. The photographs are included in an internal ANL site evaluation document prepared within one week of the site visit.

To remain abreast of the site status, the field engineer maintains monthly telephone contact with the solar site contractor. In addition, the monthly and seasonal performance reports and other data are monitored through the National Solar Data Network (NSDN).

The ANL field engineer visits the site if a component fails, the system is down for a extended period, the data being monitored at ANL indicates system degradation, or if a specific request is made by the COR/PM. The problem and the solution of the site contractor are documented. If the system problem is due to a component failure, the ANL field representative may arrange to have the contractor ship the component to ANL for failure analysis.

A.1.3 R&M Data Forms

The system operating experience and scheduled and unscheduled maintenance time are recorded on the DOE Solar Demonstration Series 50B form. These data are a part of the permanent solar site documentation and are logged into the Solar Reliability and Materials Library.

Because the ANL Reliability and Maintainability Program begins to interface with the solar demonstration sites during start-up operations, the ANL field engineers on their first site visit will transcribe all available data from the log of the owner/operator on the series 50B forms. Each problem and its resolution by the site owner/operator will be recorded separately.

To maintain up-to-date site information on reliability and maintainability, the ANL field engineer leaves additional series 50B forms for the contractor to complete and mail to the ANL program office. Also, the site owner/operator can use the ANL toll-free number to transmit the information.

A.1.4 Data Evaluation

The field data obtained during this program are reviewed, transferred to computer coding forms, and stored in the Solar Reliability and Maintainability Library for later analysis. These field data are used to:

- Identify generic solar energy system problems
- Compile failure statistics for use in system reliability assessments.

A library software package is used to scan the incoming data and to show whether a problem is recurring. When the frequency of occurrence indicates that more that 10% of similar sites could be affected, a Failure Prevention Bulletin will be developed to alert the contractors about the problem.

A.1.5 Further Reading on ANL Reliability/Maintainability Programs

Preliminary Evaluation of Selected Reliability, Maintainability, and Materials Problems in Solar Heating and Cooling Systems. ANL/SDP-TM-78-2; SOLAR/0900-78/70. Argonne, IL: September 1978.

Reliability and Maintainability Evaluation of Freezing in Solar Systems. ANL/SDP-TM-78-3; SOLAR/0901-78/70. Argonne, IL: September 1978.

Reliability and Maintainability Evaluation of Solar Collector and Maniford Interconnections. ANL/SDP-TM-79-4; SOLAR/0902-79/70. Argonne, IL: March 1979.

Reliability and Maintainability Evaluation of Solar Control Systems. ANL/SDP-TM-79-5; SOLAR/0903-79-70. Argonne, IL: March 1979.

Influence of Solar-Fluid Properties on Thermal Performance Based on National and Measured Values. ANL/SDP-TM-79-6; SOLAR/0904-79/70. Argonne, IL: May 1979.

Preliminary Evaluation of Rate of Solar-Fluid Scaling on Thermal Efficiency. ANL/SDP-TM-79-7; SOLAR/0905-79/70. Argonne, IL: August 1979.

APPENDIX B

RELIABILITY ENGINEERING ACTIVITIES IN THE NATIONAL PHOTOVOLTAIC PROGRAM*

This appendix will outline the more significant reliability engineering activities being performed in support of the National Photovoltaic Program. Two photovoltaic array design approaches are being followed in solar electric power systems development—concentrator arrays and flat-plate modules/arrays. Goals have been established by DOE in two areas: cost and reliability. Goals for cost are expressed in time-phased dollars per peak watt($/$W_p$), so that there are specified low $/$W_p$ values for 1982 followed by still lower $/$W_p$ values for 1986. The reliability goals are in terms of lifetime: a 20-year minimum lifetime is stipulated.

This appendix will discuss the reliability engineering activities of three subdivisions of the National Photovoltaic Program in support of these goals. The three subdivisions are:

- Concentrator Arrays
  Reliability activities under
  cognizance of Sandia Laboratories
  Albuquerque, N. Mex.
- Flat-Plate Arrays
  Reliability activities under
  cognizance of Jet Propulsion Laboratory (JPL)
  Pasadena, Calif.
- Field Application/Demonstration Site Monitoring
  Reliability activities under cognizance of
  Massachusetts Institute of Technology/Lincoln
  Laboratories (MIT/LL).

The reliability engineering activities in this appendix are not a complete list of upgraded programs of each organization, but are an outline of the scope of reliability work being performed.

B.1 RELIABILITY ACTIVITIES ON CONCENTRATOR ARRAYS

Photovoltaic power systems of the concentrator array design approach are only now becoming operational and have not yet been installed in field demonstration sites. The focus in reliability of concentrator arrays has been testing for component performance and reliability/durability. Test programs have been developed for concentrator optics, tracking systems, concentrator cells, and design elements used in both heat sinking and electrical contacting of the array. The three types of tests that are being performed are constant temperature aging, temperature-humidity cycling, and temperature-illumination aging.

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*See end of this appendix for references that give further details of the photovoltaic system reliability program at Jet Propulsion Laboratories.

Additional reliability activities at Sandia include tests that will help to determine degradation of plastics and adhesives to ultraviolet light, the effect of wind and loading stresses on array mounting/tracking system, and resistance of cell encapsulants/optical components to dust abrasion and hail impact.

A major new complex developed at Sandia will test complete concentrator array systems and will include facilities to test power conditioning and battery storage elements of photovoltaic systems. System test plans call for use of solar simulators so that 24-hour testing can be carried out.

B.2 RELIABILITY ACTIVITIES ON FLAT-PLATE ARRAYS

A spectrum of reliability engineering activities is being performed by JPL on the Low—Cost Solar Array (LSA) Project supporting development of flat-plate module/array designs. The overall LSA approach is to improve reliability of flat-plate modules by developing and then employing criteria that force iterations of designs.

The LSA reliability program on flat-plate modules includes:

- Specification Generation
- Module Qualification Testing
- Field Testing
- Reliability Analysis and Prediction Studies
- Life Prediction Studies
- Problem/Failure Reporting System
- Failure Analysis
- Quality Assurance
- Component Testing.

Other aspects of the LSA reliability program include activities to accomplish three objectives: to understand failure definitions and mechanisms at the component level; to develop improved testing methods appropriate to reliability of photovoltaics; and to develop new, more effective techniques for reliability trade-off analysis and prediction.

In the LSA Project most of the reliability activities are performed in the Engineering Area, Operations Area, and Encapsulation Task, a subdivision of Technology Development Area. Other areas of LSA such as Quality Assurance and Production Process and Equipment also provide substantial reliability-related inputs (see Figure B-1).

B.2.1 Specification Generation

A basic tool in controlling reliability of flat-plate photovoltaic modules is the development and use of design specifications both by LSA and most federal and commercial users. In the evolution of improved module designs JPL/LSA has made large procurements from industry (referred to as a "Block" buy). Each one of four procurements followed the previous one by approximately a year; i.e., Block I, Block II, Block III, and

- INCLUDES RELIABILITY ENGINEERING FUNCTION - PART OF LSA ENGINEERING AREA ORGANIZATION
- INCLUDES BOTH IN-HOUSE (LSA/JPL) AND CONTRACTOR-SUPPORTED ACTIVITIES
- INCLUDES CONTRIBUTIONS TO RELIABILITY ACTIVITY BY SEVERAL ORGANIZATIONS WITHIN LSA PROJECT
- RELIABILITY PROGRAM SPANS END-TO-END

  i.e., RELIABILITY ACTIVITIES IN EACH MAJOR PROJECT PHASE

  - PRELIMINARY DESIGN
  - DESIGN
  - PRODUCTION
  - FIELD DEMO SITES (DATA COLLECTION)
  - DATA ANALYSIS
  - FEEDBACK TO ORIGINAL DESIGNERS

Figure B-1. FLAT-PLATE ARRAY RELIABILITY ACTIVITIES KEY FACTORS IN LSA FLAT-PLATE RELIABILITY PROGRAM (Source: JPL)

Block IV (see Figure B-2). Most major users of flat-plate photovoltaics (i.e., Federal Photovoltaic Utilization Program and private industry) also employ JPL/LSA specifications, and this wide acceptance has helped to improve reliability.

B.2.2 Module Qualification Testing

Flat-plate photovoltaic modules procured by LSA are qualification tested as part of vendor approval. The reliability engineering inputs involve developing and supplying environmental test requirement levels, test methods, and analysis of the data. Each new round of qualification test of modules involves updating of the requirement based on results obtained from the previous round.

B.2.3 Field Testing

JPL is aware of 26 different flat-plate module field test sites located throughout the western hemisphere from Panama to Alaska. These sites provide environmental extremes that complement the more limited number of system-level experiments. The data obtained from these sites, which are monitored periodically, serve as input to reliability analysis studies and design improvements.

B.2.4 Reliability Analysis and Prediction Studies

As a part of the LSA reliability effort, a range of reliability analysis and prediction studies have been performed or are being performed (see Figure B-3). These studies directly support the cell/module/array design effort. Results derived are used for trade-offs and optimization of designs. Some representative LSA reliability engineering analyses on flat-plate designs are as follows:

- Series-parallel reliability model of overall array to the cell level;
- Determination of array sensitivity to known component failure modes;
- Array/module circuit configuration guidelines to minimize array degradation owing to component failures;
- Test techniques and acquiring reliability data for module components (cells, solder joints, connectors, etc.);
- Definition of cost/benefits associated with component reliability improvements; and
- Definition of optimum maintenance practices for minimum life-cycle costs.

At the array subsystem level, a program is being initiated to develop inputs to support reliability allocations/apportionments. This has resulted in a program to obtain failure rate data on components used in module designs (i.e., cells, cell interconnects, solder joints, etc.). At the system level, no reliability allocations/apportionments have been developed.

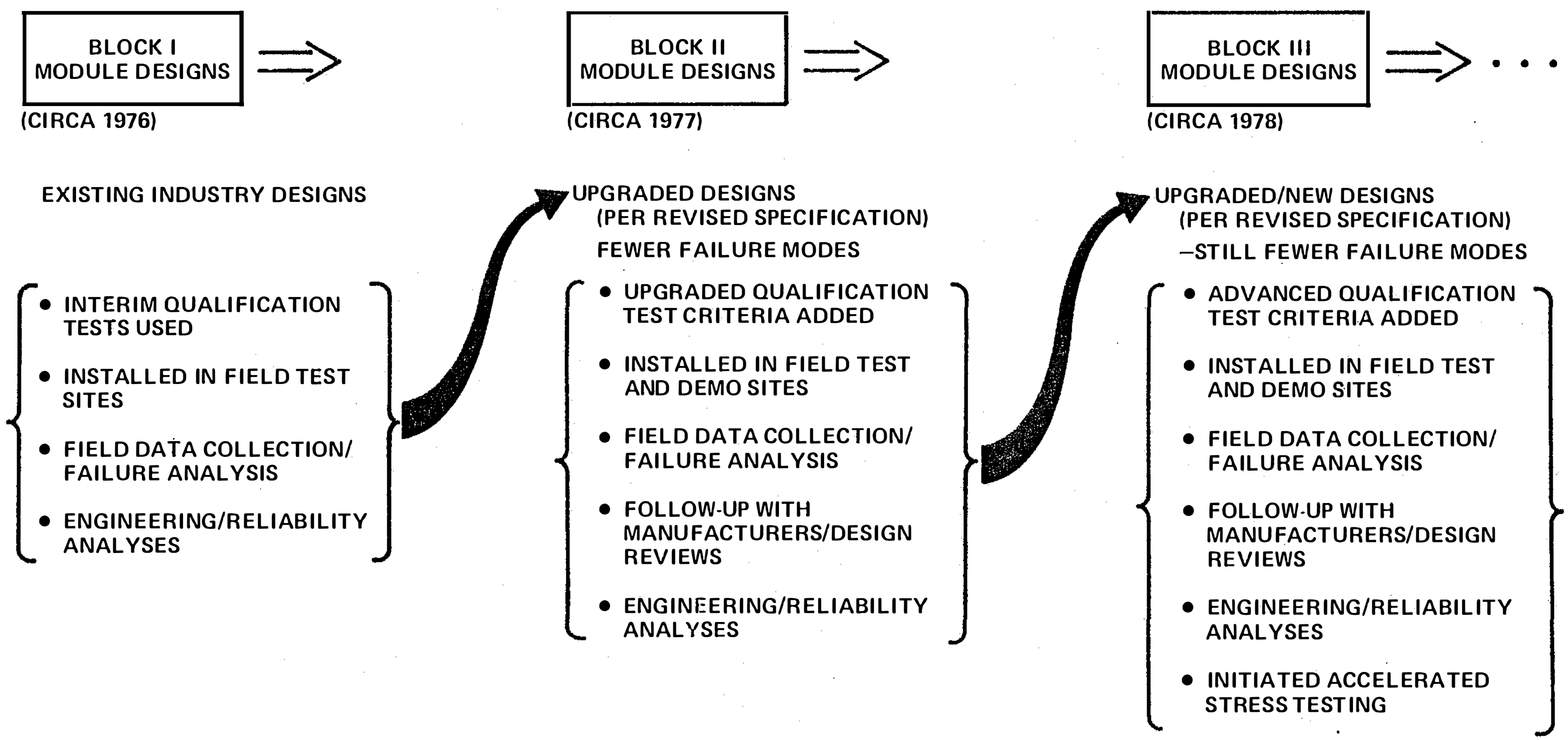

Figure B-2. LOW-COST SOLAR ARRAY PROJECT APPROACH (Source: JPL)

CATEGORIES OF WORK INCLUDE:

- RELIABILITY ALLOCATION/APPORTIONMENT STUDIES (REQUIRED FOR TOP-DOWN REQUIREMENTS DEVELOPMENT)
- DESIGN TRADEOFF STUDIES
- RELIABILITY PREDICTION ANALYSES
- FAILURE MODES, EFFECTS AND CRITICALITY ANALYSES
- MODULE/ARRAY DESIGN OPTIMIZATION STUDIES
- LIFE CYCLE COST MODEL INPUTS

Figure B-3. FLAT-PLATE ARRAY RELIABILITY ACTIVITIES RELIABILITY ANALYSIS/STUDIES ACTIVITY (Source: JPL)

B.2.5 Life Prediction Studies

Within the LSA Encapsulation Task, a major body of work is directed toward a life-prediction model (LPM) for photovoltaic module encapsulation material systems. The model being developed will predict module lifetime distribution in terms of a specified performance decrement or failure rate. The life expectancy of photovoltaic modules is now unknown. The desired lifetime minimum of 20 years has resulted in an effort composed of both analytical and laboratory testing activities. In the testing activity, both real time and accelerated aging testing are being performed.

There is also the search for a recommended low cost and reliable encapsulation system for photovoltaic module designs. The Encapsulation Task has worked closely with reliability engineering to develop and interchange baseline reliability data on unencapsulated cells. The information exchange with the encapsulation study involves both data and participation on certain test efforts.

B.2.6. Problem/Failure Reporting System

The Problem/Failure Reporting system is a cornerstone in the LSA reliability effort on flat-plate photovoltaic arrays. All modules/arrays placed on or installed in field test sites are automatically tied into the LSA project reliability engineering effort through this system of data collection and reporting. Not only are all failures documented but the system also provides for failure data storage and retrieval, return of failed parts for failure analysis, closeout of the problem/failure and a feedback loop built in to allow the original designer to be aware of the problem/failure (see Figure B-4).

B.2.7 Failure Analysis

A complete failure analysis laboratory including capabilities in such areas as electrical, mechanical, chemical, fracture mechanics/material analysis, etc., supports the Operations Area of the project. There is a direct interface between the reliability engineering function and this laboratory. As a line function supporting the problem/failure reporting system, most failed modules are returned to JPL. The failure analysis laboratory has made many major reliability contributions; i.e., in problems such as cell cracking, high voltage withstand/corona discharge, causes of cell reverse biasing, validation of encapsulation material delaminations observed in the field, etc.

B.2.8. Quality Assurance

In any new and immature industry such as solar photovoltaics, workmanship and quality assurance problems have been major factors. Failures from workmanship often outnumber failures from design. LSA Quality Assurance supports each manufacture of Block procurements with 100% module final inspection. Quality assurance periodically reports its finding on each module type (expanded and/or collected by quantity and various modes of failure) observed by the JPL inspectors.

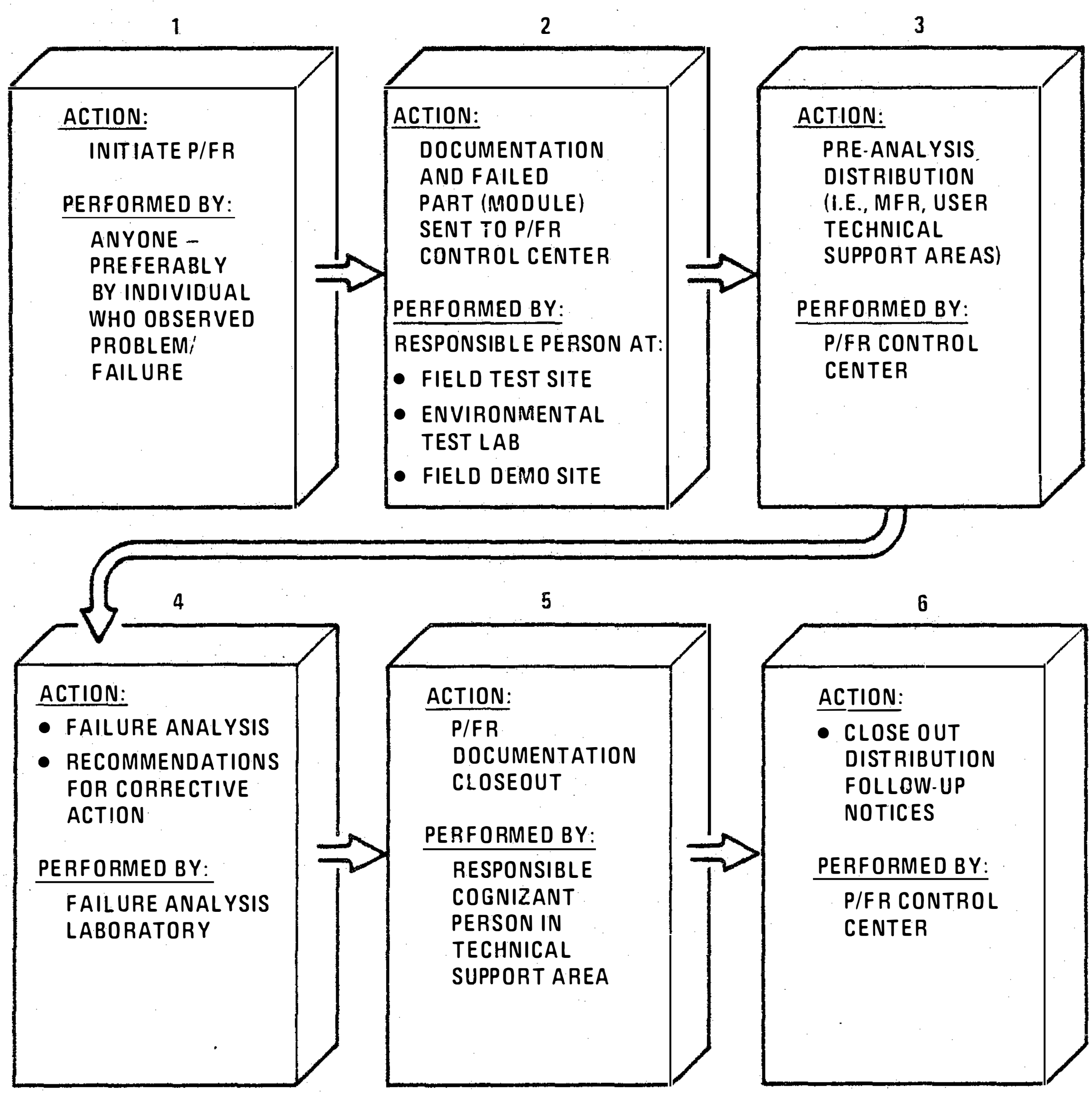

Figure B-4. LOW-COST SOLAR ARRAY PROJECT PROBLEM/FAILURE REPORTING SYSTEM P/FR PROCESS SEQUENCE (Source: JPL)

B.2.9 Component Testing

A major part of the reliability effort is component testing and generation of basic reliability data at the component level. Fracture mechanics and accelerated stress testing are being performed on various types of components; i.e., cells. The objectives of these tests are twofold: to obtain insight into reliability attributes and to develop testing methodologies for future test requirements.

B.3 FIELD APPLICATION/DEMONSTRATION SITE MONITORING

MIT/LL is responsible for field application site monitoring, which is directly tied to the JPL/LSA Problem/Failure Reporting System so that component (module) failures/degradations observed are documented and incorporated. "Failed" modules may be removed and returned to JPL for failure analysis. Many of the "failures" observed by personnel from MIT/LL would not be caught were it not for this periodic in-the-field monitoring program.

Photovoltaic modules/arrays, specifically flat-plate designs having considerable field application exposure, do not seem to experience many catastrophic failures. Because the predominant failure has been the degradation type, periodic monitoring of field application/demonstration sites is important in the overall reliability programs on photovoltaic arrays.

The MIT/LL field site monitoring program involves:

- Periodic visits to photovoltaic array sites (search for failed modules)
- Failed modules removed
- Nondestructive failure analysis performed (interim)
- Failed modules sent to LSA (JPL) for complete failure analysis
- All observed failures documented into the Problem/Failure Reporting System.

B.4 CONCLUSIONS

By being decentralized and close to their respective design activities, the reliability engineering activities on the National Photovoltaic Program have been tailored to the needs of each project. For concentrator arrays, reliability activities have been focused on performance and durability testing of components prior to field application installation. For flat-plate modules/arrays where the hardware is being used in the field, more complete reliability activities are being used, such as reliability analyses, component testing, specification development, field failure reporting, data analysis, etc. For field site monitoring, detailed and sophisticated procedures have been developed. Data analyzed by the appropriate organization could be useful if it were made available to other segments of the program.

B.5 FURTHER READING ON RELIABILITY STUDIES IN THE JET PROPULSION LABORATORIES PROGRAM

Methodology for Designing Accelerated Aging Tests for Predicting Life of Photovoltaic Arrays. ERDA/JPL-954328-77/1. Pasadena, CA: February 1977.

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"Review of World Experience and Properties of Materials for Encapsulation of Photovoltaic Arrays." ERDA/JPL-954328-76/4. Pasadena, CA: 31 July 1976.

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U.S. DOE. Evaluation of Available Encapsulants for Low Cost, Long Life Silicon Arrays. JPL-9543282. Pasadena, CA: June 1978.

Proceedings of the 13th LSA Project Integration Meeting. DOE/JPL 1012-29. Pasadena, CA: April-August 1979.

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15. Supplementary Notes

16. Abstract (Limit: 200 words)

A workshop to reveal the scope of reliability-related activities in solar energy conversion projects and in nonsolar segments of industry is described. Two reliability programs, one in heating and cooling and one in photovoltaics, are explicated. This document also presents general suggestions for the establishment of a unified program for reliability, durability, maintainability, and safety (RDM&S) in present and future solar projects.

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