Preliminary Reliability and Availability Analysis of the Heber Geothermal Binary Demonstration Plant

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ABSTRACT

This report presents an assessment of the reliability and availability of the Heber
Geothermal Binary Demonstration Plant on the basis of preliminary design information.
It also identifies and ranks components of the plant in order of their criticality
to system operation and their contribution to system unavailability. The sensitivity
of the various components to uncertainties of data and the potential for reliability
growth are also examined. The assessment results were obtained through the adapta-
tion and application of an existing reliability and availability methodology to the
Heber plant design. These preliminary assessments were made to assist (1) in eval-
uating design alternatives for the plant and (2) in demonstrating that the closed-
loop, multiple-fluid, binary cycle geothermal concept is competitive with the more
conventional flashed steam cycle technology.

The Heber Geothermal Binary Demonstration Plant Project is a cooperative effort of
the Department of Energy, the Electric Power Research Institute, the San Diego Gas
and Electric Company, and other organizations directed toward accelerating geothermal
development for power generation and establishing the binary cycle technology as a
proven alternative to the flashed steam cycle for moderate temperature hydrothermal
resources. The binary power plant would have a capacity of 45 MW_e net and would
derive its energy from the low salinity (14,000 ppm), moderate temperature (360°F,
182°C) fluid from the Heber reservoir in southern California.

EPRI PERSPECTIVE

PROJECT DESCRIPTION

This final report on RP1900-2, entitled Preliminary Reliability and Availability
Analysis of the Heber Geothermal Binary Demonstration Plant, is a joint effort of
the Geothermal Power Systems Program and the Reliability Subprogram of the Advanced
Power Systems Division.

This project was an application of reliability and availability models that were
developed and maintained by the Advanced Power Systems Division to help assure that
all systems are evaluated on a consistent basis and to enhance the success of
individual projects within the division. The analysis was based on preliminary
design information. The reliability-availability model was adapted for use in this
project from a model originally developed by the ARINC Research Corporation, and
failure rate data were derived from a variety of sources including two electric
power utilities, the North American Electric Reliability Council, manufacturers,
users, and others. Availability sensitivity to component failure rate was analyzed,
and an estimate of reliability growth potential was developed.

PROJECT OBJECTIVES

The project was undertaken to assess the probable reliability and availability of a
binary-cycle geothermal power plant of advanced design. The purpose of the assess-
ment was to help develop a philosophy for an availability enhancement program. In
the demonstration plant, heat is exchanged between the geothermal fluid, a hot
brine, and a secondary working fluid, a hydrocarbon, which drives the turbine.

PROJECT RESULTS

This binary plant appears to be capable of higher reliability and availability than
otherwise comparable single-fluid geothermal units. The long-term effectiveness is
estimated at 80.5% (a measure equivalent to availability but not including scheduled
maintenance). It is expected that this can grow to 89.7% within 10 years by making
certain modifications and additions.

These results are based on a limited quantity of data gathered during this study. However, sensitivity analyses have shown how results vary if the data used are significantly different. For example, the data used for the brine-hydrocarbon heat exchangers are a mean time between failures (MTBF) of 1980 hours and a mean time to restore (MTTR) of 168 hours. If either the MTBF or the MTTR are improved by a factor of 4, the system effectiveness increases by 4.4%. The long-term effectiveness value of 80.5% would go to 84.9% if the exchangers are 400% better, i.e., a MTBF of 7920 hours, or to 67.1% if they are 75% worse, i.e., a MTBF of 495 hours. Although the heat exchangers are the most sensitive subsystem, other subsystems are fairly sensitive as well. As a consequence, it is important to improve the accuracy of the data base by additional work, such as failure modes and effects analyses, or with additional data from designers, manufacturers, and users.

Jerome Weiss, Project Manager
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SUMMARY

The assessment methodology employed in this study was developed under EPRI Contract
RP 1461 and adapted for use in the reliability and availability assessment of the
Heber Geothermal Plant. It had also been previously used to analyze gasification
combined-cycle (GCC) and advanced coal-fired plant (CFP) designs, as well as a number
of operational oil-fired and gas-fired combined-cycle plants. EPRI contracted with
ARINC Research Corporation (1) to adapt its assessment methodology to the Heber
binary cycle design so that initial baseline estimates of the plant reliability and
availability could be obtained, and (2) to develop an operating model that could be
used in evaluating design alternatives and obtaining updated assessments of the
expected plant performance as the design evolves.

The specific objectives of the project are as follows:

- To develop a computer-based reliability and availability assessment
  model of the Heber design

- To exercise the model to obtain baseline estimates of the plant
  reliability and availability

- To determine the sensitivity of the baseline results to data
  uncertainties

- To rank the plant components by their effect on the baseline results

- To identify potential availability improvement options

- To assess the impact of potential reliability growth on the plant's
  performance

The assessment model was based on the design illustrated in the Preliminary Design
Manual for a Geothermal Demonstration Plant at Heber, California, EPRI ER-670,
February 1978. This design uses the binary cycle to develop 45 MW_e of output power
from the moderate temperature brine of the Heber geothermal reservoir. It is recog-
nized that the final design may differ significantly and that subsequent iterations
of the assessment may be desirable.

The study consisted of the following interrelated tasks:

- Characterize the plant design and equipment

- Define system states, fault trees, and state definitions

- Develop component failure and repair data base

- Adapt and apply the assessment model

- Develop reliability growth estimates and assess their impact

- Prepare final report

On the basis of the preliminary design, the plant was partitioned into seven independent subsystems (ISSs). A fault tree (described in Section 2 of this report) was developed for each subsystem to relate the occurrence of a top-level event (e.g., subsystem failure) to the individual components within the subsystem that could cause the event. Probability expressions were then developed for each subsystem type, based on fault trees and available data, which represent the probabilities of the top-level events as a function of the constituent component failure and repair characteristics.

System states and their associated capabilities were defined in terms of the operational conditions of the seven identified ISSs. Twenty-five system states and their associated availabilities were defined with the assistance of the Ben Holt Company. The individual subsystem expressions were then used, in conjunction with the state definitions, to define probability expressions that represent the likelihood of moving from each defined state to each other possible state, or remaining in the same state in a given short interval of time. This resulted in a 25-by-25 matrix of expressions, called the transition matrix, which was used in the assessment model.

A component failure and repair data base was then developed. For a number of unavoidable reasons, this data base consisted of extrapolations of available data combined with estimates by consensus from the knowledgeable personnel in the organizations contacted.

A program designed for interactive time-share computer application was developed to determine the reliability and availability assessments and to perform sensitivity analyses. Baseline reliability and availability assessments were made by using the acquired data base, and component rankings were developed following sensitivity analyses. Finally, components with potential reliability growth were identified; a time-phased scenario of the growth was hypothesized; and the program containing data for the improved components was used to produce an estimate of the potential availability growth with time.

Baseline evaluations of reliability and availability were obtained by using the data base and by exercising the assessment model. One measure of inherent reliability (the time for the plant to decrease from 100 percent to 50 percent expected capacity in the absence of corrective maintenance) was 37.5 days. Comparable values obtained from assessments of GCC and CFP designs were about nine days and eight days, respectively. Similarly, the availability assessment was found to approach a steady-state value of about 81 percent. The corresponding GCC and CFP availability measure values were 79 percent and 82 percent, respectively. The most likely state is the "all up" state (State 1), with an availability of 34.2 percent. Further, the probability of at least 75 percent capacity is 0.71 and the probability of a full outage is approximately 0.02. Finally, it was determined from the results of the baseline assessment that the probability of 100 percent capacity for five days was 0.885 and the probability of at least 75 percent capacity for 60 days was 0.725.

Sensitivity analyses were performed to determine the effect that changes in the baseline data would have on the resultant steady-state effectiveness (availability measure) value. Component rankings were developed in accordance with the following criteria:

- Power Lost -- the increase in steady-state effectiveness when a component is considered to be perfect (i.e., it is assumed to be failure-free).

- Availability -- the change in steady-state effectiveness per change in component availability.

- Failure Rate -- the change in steady-state effectiveness per change in component failure rate.

- Mean Time to Restore -- the change in steady-state effectiveness per change in component mean time to restore.

The resultant rankings indicate that the heat exchanger represents the most sensitive component, whereas the circulating water pump and motor have a comparatively negligible impact.

As a part of the baseline data-collection effort, potential areas of reliability improvement were investigated and source estimates of expected growth were obtained. It was determined that potential growth opportunities existed for six of the seven subsystems. Implementation of the identified improvements, coupled with reliability growth estimates by the sources, would increase the steady-state effectiveness by about nine percent over a ten-year period. In addition, further growth could be achieved by introducing bypass capabilities in the heat exchanger and the

condenser/accumulator subsystems. This, for example, would permit operation of the plant in additional higher-capacity states when a failure occurs in a heat exchanger rather than losing the entire subsystem and dropping to 50 percent capacity.

Evaluation of the Heber design, using the baseline data, produced reliability and availability estimates that were equal to or better than previously evaluated GCC and CFP designs. The heat exchanger has the greatest impact on the availability measure. An additional nine percent growth in availability could be realized through a combination of expected component reliability growth and the improvements resulting from the implementation of several design changes.

Section 1

INTRODUCTION

This report presents the results of a six-month investigation of the expected reliability and availability of the proposed Heber Geothermal Binary Demonstration Plant. The investigation was conducted by ARINC Research Corporation for the Electric Power Research Institute (EPRI) as part of EPRI Research Project 1900. Contract RP 1900-2 was administered under the technical direction of both Mr. Jerome Weiss of EPRI's Advanced Power Systems Division and Mr. Vasel Roberts, EPRI Heber Project Manager.

BACKGROUND

In 1976 EPRI initiated feasibility studies of the Heber Geothermal Binary Demonstration Plant Project. The primary purpose of the project was to accelerate geothermal development for electric power generation in the United States by developing a power conversion system having high-resource-utilization efficiency for a moderate temperature, low salinity, hydrothermal power plant. This project was to demonstrate power conversion technology, environmental control technology, and the economics of power generation. A second objective was to establish the binary cycle technology as a proven alternative to the flash steam cycle for those applications in which reservoir characteristics and site specific considerations make closed-loop systems more desirable. The documentation of technical studies, analyses, and evaluations, and the dissemination of that information were also considered important objectives.

The plant is to be located at the Heber geothermal field in the Imperial Valley of southern California. Its design is based on a binary fluid conversion cycle wherein a saturated hydrocarbon is utilized as the secondary working fluid. The primary geothermal fluid (brine) will be supplied from an adjacent production facility. The hot brine will be delivered to the power plant boundary in the saturated liquid phase. Following the transfer of heat energy from the geothermal fluid to the hydrocarbon working fluid in heat exchangers, the brine will be returned for injection into the Heber reservoir. The hydrocarbon will vaporize in the heat exchangers and then drive a turbine/generator to produce electrical energy.

The preliminary design work that was undertaken following the feasibility study and completed in 1977 formed the basis for this analysis. Because of funding difficulties the project was dormant from 1978 to 1980, at which time the detailed design effort was resumed. This analysis, based on the earlier preliminary design effort, was undertaken to develop inputs to the detailed design effort as a part of a reliability and availability enhancement program for the project. It is likely that the final design may differ significantly from the preliminary design and that subsequent iterations of the analysis may be desirable.

PROJECT SCOPE

The reliability and availability assessments in this project were developed on the basis of preliminary design data and the best failure and repair data that were available during the period of the contract. Both EPRI project management and ARINC Research recognized that this early assessment might lack precision but would provide an insight into potential problem areas that might be corrected as a result of timely identification. This project included identifying and obtaining sufficient data and performance measures so that it would be possible to make an adaptation and application of a reliability and availability assessment model, which was previously developed for EPRI for application to other power plants. In the absence of specific data, expert opinion from knowledgeable sources was to be used in performing the baseline assessments and in estimating possible areas for reliability growth.

PROJECT OBJECTIVES

The specific objectives of the project are as follows:

- To perform initial reliability and availability assessments of the Heber plant design

- To identify and rank components of the Heber plant in order of their criticality to system operation and their contribution to system unavailability

- To determine the sensitivity of the plant availability to data uncertainties

- To recommend changes to the design to improve the plant's reliability and availability

- To predict the effects of reliability growth of components on plant performance

This project was intended to provide an early insight into the reliability and availability characteristics of the proposed Heber geothermal plant. The predictions that resulted from the analysis are not precise, because a statistically valid data base

is not yet available. The analyses were expected to provide reasonable values and uncertainties associated with those values, sensitivities of results to uncertainties in the data, identification of critical components and their impact on reliability and availability, a guide to future data needs and recommendations for improving the data base, and recommendations for improving system reliability and availability. The data collection and development effort was also expected to result in a preliminary data base that would be as consistent as possible and that could be expanded and improved as field data become available.

REPORT ORGANIZATION

Section 2 of this report describes the project tasks and subtasks, including an overview of the technical approach, the design of the plant; fault tree analyses and modeling methods; and the efforts involved in data collection. Section 3 describes the data base, the underlying assumptions used in the analysis, and the results of the assessments performed. These results include a baseline set of results as determined from the present design and data, an assessment of potential reliability growth, and the impact of this growth. In Section 4, the results are interpreted, conclusions are described, and recommendations are presented. Appendixes A through D present the fault trees developed for the preliminary design, sources for the data base used in the analysis, the computer program used in the analysis, and the mathematical expressions used in ranking the components in order of their criticality to plant performance.

Section 2

TECHNICAL APPROACH

This section presents an overview of the technical approach and a description of the tasks required to perform this project. In addition, a description of the plant design, the subsystem fault trees and system state definitions, and the adaptation of the reliability, availability, and maintainability (RAM) analysis model are also presented. This section concludes with a general discussion of data collection efforts.

OVERVIEW OF THE APPROACH

The project, as illustrated in Figure 2-1, consisted of six interrelated tasks:

- Task 1: Characterize the Plant Design and Equipment (Configuration)

- Task 2: Construct Fault Trees for the System

- Task 3: Collect Data and Develop a Data Base

- Task 4: Adapt and Apply the RAM Model

- Task 5: Develop and Incorporate Reliability Growth Estimates

- Task 6: Prepare Final Report
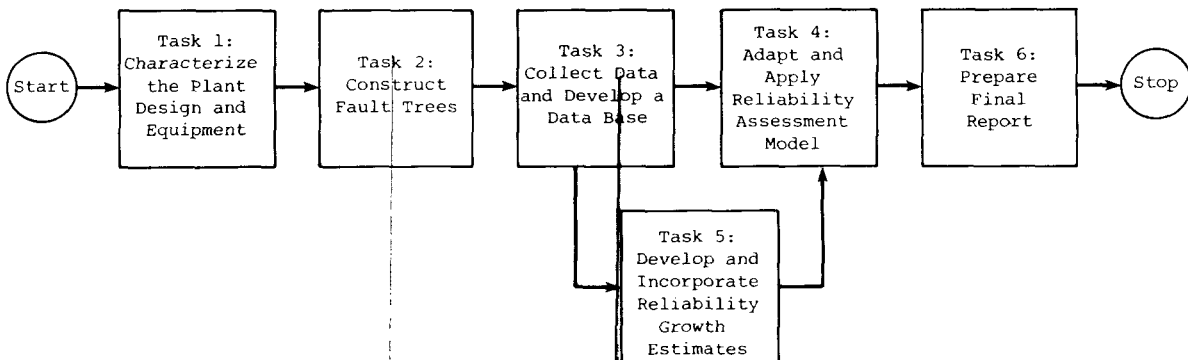
Figure 2-1. Flow Diagram of Heber Assessment Tasks

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Both EPRI and contractor assistance were required to characterize and describe the proposed plant and to obtain usable data. The plant design, described in later paragraphs of this section, was used as the baseline for the assessment. It was recognized that the design would be changing during the course of this project but, because of the limited period of performance, it was necessary to select a baseline assumption at the outset. Fault tree construction, system state and capacity definitions, and the adaptation and application of the RAM model all followed the general experience of earlier* EPRI work. Estimating and assessing the impact of reliability growth and improvements was based on a knowledge of probable failure modes and causes, those measures which might be applicable to mitigate their effects, and assistance from expert sources contacted. Each of the tasks and their associated subtasks are discussed in greater detail in the following paragraphs.

Task 1: Characterize Plant Design and Equipment

The objectives of Task 1 were to characterize the plant design and its equipment, to partition the plant design into independent subsystems, and to define the system states and related capabilities. To accomplish these objectives, this task was divided into the following major subtasks:

- Subtask 1A: Obtain and Review Plant Design and Equipment Data

- Subtask 1B: Partition the Plant Design into Independent Subsystems

- Subtask 1C: Determine the Number of System States and Their Associated Capabilities

Subtask 1A: Obtain and Review Plant Design and Equipment. The review was based on EPRI Report ER-670, Preliminary Design Manual for a Geothermal Demonstration Plant at Heber, California, Topical Report on Project 580, Holt/Procon, February 1978. This design and equipment description was subsequently supplemented by discussions with some of the contractors identified in Appendix B and by EPRI Report ER-1099, Heber Geothermal Demonstration Power Plant, Final Report on Project 580-2, Fluor Engineers and Constructors, Inc., June 1979. The review consisted primarily of developing an understanding of the equipment in terms of types of use, service, and functional characteristics. These were necessary steps to permit application of the first step in the analysis method -- the partitioning of the system into independent subsystems.

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*EPRI AP-1610, Guide for the Assessment of the Reliability of Gasification-Combined-Cycle Power Plant, ARINC Research Corporation, November 1980, and EPRI AP-1643, Development of a Reliability Prediction Methodology for a Gasification-Combined-Cycle Power Plant, ARINC Research Corporation, November 1980.

Subtask 1B: Partition the Plant Design into Independent Subsystems. The method for partitioning the plant into independent subsystems is described in detail under "Plant Design Description" (page 2-8). In general, the approach is to partition the plant equipment into groups of identical equipments that perform a distinct and separate function in the process. For purposes of the analysis and to fit the RAM model structure, these groups are assumed to be independent subsystems. This partitioning then permits the identification of the number of possible, nonambiguous states that the system may assume in operation and permits a corresponding capacity for each system state to be identified. Subtask 1B followed a methodology described in detail in EPRI Report AP-1610.

Subtask 1C: Determine the Number of System States and Their Associated Capabilities. Each independent subsystem was assumed to have a linear relationship to total plant capacity based on information supplied by the system designer and EPRI. Each independent subsystem (hereinafter called ISS) was considered to be either operating or nonoperating, with no partially operating states permitted except where the ISS contained a number of identical components in parallel. The number of possible nonambiguous states in combination for all of the ISSs were then tabulated. For each state identified, a corresponding plant power output was determined. This effort is discussed under "Fault Trees and System States" of this section.

Task 2: Construct Fault Trees for the System

A fault tree is a graphic representation that depicts the relationship of events that may occur to a system and its components. Fault trees were developed for each ISS to relate the occurrence of top-level events and events that contribute to each top-level event. This analysis divided each ISS into components that contributed to a top-level event -- either a failure or a repair. The "tree" structure is carried out until there are insufficient data to assign failure or repair times to each block of the tree. This analysis then permits the development of mathematical expressions of failure and repair probability. These probabilistic expressions are the algorithms used in the computer program to determine the relationship of transitions from one state to another state as components and subsystems fail and are repaired. Task 2 subtasks are described in the following paragraphs.

Subtask 2A: Identify Top-Level Events and the Major Components for Each ISS. The failure or repair of each ISS is the top-level event of interest. In identifying the major components of each ISS, the contribution of each component to the top-level event is determined. For example, if an ISS consists of three major components any one of which can fail the ISS, the top-level event occurs if any of the three

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Lower order events occur (see Appendix A). However, if the ISS operates unabated with only two of the three major components operating, the top-level event cannot occur until both major components fail. Identification of the events and components is necessary for the construction of fault trees.

Subtask 2B: Develop Fault Trees. The ISS Fault trees comprise the components of each subsystem type in the ISS. These fault trees illustrate the relationship of all of the components to the ISS. This subtask aids in identifying the level to which the analysis can be taken. In general, the more detailed the fault tree, the more accurate the analysis. Since failure and repair times are associated with each block in the tree, data limitations will restrict the detail of the fault trees. It is theoretically possible to generate extremely complex and detailed fault trees; however, if supporting data for each block are not available, then these details are of little value. It can be assumed that the failure and repair rates assigned to each block of the tree account for all the failures and repairs that could occur at all lower levels. This assumption both simplifies the analysis and indicates an area for improvement when limited data are available. The fault trees are employed to obtain probabilistic expressions of top-level events (either failure or repair) in terms of reliability and maintainability functions. These expressions are then incorporated into the model.

Subtask 2C: Develop State Transition Probability Expressions. All significant system states were identified and described by first defining State 1 as the condition in which all subsystems are operating. Then, each subsystem of each ISS is considered to fail in turn or to remain operating to define the subsequent degraded states. When all the possible combinations were exhausted, i.e., all possible states defined, these states were then related to plant capability -- the estimates of power output in each state. These state definitions were used as elements of the transition expressions and were then entered into the structure of the model.

In this case, the model is a structured representation of the plant that employs a mathematical rather than a graphical presentation. To compute the probabilities of various component groupings, the model uses numerical data derived from component failure and repair rates. It depicts the actual operation of the plant as a continuous process in which the plant passes from one state to another, subject to the probabilities involved. The probabilities define the likelihood of the plant moving from one state to another (e.g., from State 1 to State 2, given that it started in State 1) and are contained in the state-transition matrix, the dimensions of which are the number of possible system states.

When the model is exercised, plant output can vary both up and down. The state-transition matrix contains the probabilities associated with the plant changing from one state to another. In notation form, the various transition probabilities are represented by (T) and subscripted to indicate the beginning and ending states. Thus $T_{1,1}$ is the probability of the plant's remaining in State 1 during a specific time interval, while $T_{1,2}$ is the probability of the plant's beginning a specific time interval in State 1 and beginning the next time interval in State 2. Specific expressions were developed for the probability of the system's moving from every possible state to every other state.

Task 3: Collect Data and Develop a Data Base

The objectives of Task 3 were to identify the components for which failure and repair data were needed and the possible sources of these data, and to collect the available data. Given data from all available sources and estimates of missing (but needed) data, these data were then used as the basis for estimates of failure and repair measures necessary to the operation of the RAM assessment model. Task 3 was divided into three subtasks:

- Subtask 3A: Identify Data Requirements and Sources

- Subtask 3B: Acquire and Assess Available Data

- Subtask 3C: Develop Failure and Repair Estimates

Each of these subtasks is described in the following paragraphs.

Subtask 3A: Identify Data Requirements and Sources. The fault tree graphic representations determined the components for which data were desired. In addition, the previously cited Heber Design Manual defined the boundary conditions of operation. Standard industry, utility, and manufacturing sources were contacted, as well as EPRI and several architect-engineer organizations. Generally, data were not readily available as discussed in subsequent paragraphs of this section. Data sources who provided information used in the study are listed in Appendix B of this report.

Subtask 3B: Acquire and Assess Available Data. Data for major components of the type to be used in the proposed Heber design were not readily available. Data were available for some similar components that could be extrapolated for the Heber application. Where no data were available but were necessary to the analysis, some estimates from knowledgeable personnel were solicited for use. This absence

of data for advanced technology designs was expected. To understand the impact of uncertainties in data, sensitivity analyses were performed, as described in the discussion of Subtask 4C (page 2-7).

Subtask 3C: Develop Failure and Repair Estimates. Data requested from manufacturers, designers, EPRI, and appropriate national organizations were reviewed and assessed. Failure and repair estimates for each major ISS component were either derived from data estimates by knowledgeable personnel or from available operating experience data. The resulting estimates of failure and repair rates were assigned to each applicable block of the ISS fault trees for use in the computer program. The fault tree levels of detail exceeded the availability of data or estimates such that the desired level of detail was not achieved. However, the level used was sufficient to the analysis.

Task 4: Adapt and Apply the RAM Model

The reliability, availability, and maintainability (RAM) assessment model employed is an adaptation of the effectiveness model first used on EPRI Project RP 1461 and cited in the GCC Plant Guide (EPRI AP-1610). In addition to adapting the model to the specifics of the Heber design, the model was also used to assess the impact of reliability growth. Task 4 is divided into the following three subtasks:

- Subtask 4A: Modify the Assessment Program

- Subtask 4B: Exercise the Model to Obtain a Baseline Assessment

- Subtask 4C: Perform Sensitivity and Component Criticality Analyses

Each of the subtasks are described in the following paragraphs.

Subtask 4A: Modify the Assessment Program. The RAM assessment program first described in EPRI Report AP-1610 is constructed in a series of modules. Adaptation of the program required direct substitution of the state transition matrix, the capability matrix, and the transition probability data of the Heber design into the modular framework of the Markov chain computer program. The modified computer program is listed in Appendix C of this report.

Subtask 4B: Exercise the Model to Obtain a Baseline Assessment. Exercising the model yielded an estimate of the inherent reliability of the plant based on the best data estimates for each ISS and major component employed in the analysis. A time-varying analysis to determine a measure of availability was also performed. Further discussion of these efforts is provided under "Assessment Model Description"

of this section (page 2-14). The baseline assessment was used both as an aid in analyzing reliability growth and as an assessment of the plant's performance as configured in the preliminary design. The baseline can then be used as a basis for comparison in determining component sensitivity, criticality, and reliability growth potential.

Subtask 4C: Perform Sensitivity and Component Criticality Analyses. For each time interval in the baseline run, the model sums the contribution of each of the possible states toward the total plant capacity. From the description of the plant partitioning and the determination of system states, it can be seen that these states are related to the probability of failure and repair of each ISS and the components within the ISS. To determine sensitivity to uncertainty and to changes in the data, the availability of each ISS was varied in turn, while the remaining ISSs were held at baseline. This procedure provides an indication of the extent to which the results are sensitive to the availability of each ISS, i.e., the sensitivity of the results to uncertainties in the data. This can be illustrated graphically by a plot of the deviation of plant availability from the baseline contributed by each ISS. Steep slopes indicate greater sensitivity to data uncertainties. Therefore, if the slope is shallow, there is little need to obtain better data. Steeper slopes indicate the need for testing, design improvements, or intensified data acquisition programs. Examples of the results of this analysis are presented in Section 3.

The issue of criticality is addressed in a similar manner. Each ISS availability is held perfect in turn (100 percent available) while the remainder stay at baseline to assess the impact on plant capacity or availability. Those components having the greatest change are most critical to overall plant performance.

Task 5: Develop and Incorporate Reliability Growth Estimates

Experience dictates that the acquisition of new systems or the development of advanced technology result in early life problems that are corrected in time. These corrections produce an improvement in plant reliability and availability, which is equivalent to the concept of reliability growth. In Task 5, analysis of the plant design and component criticality identified those components which probably could be improved. Estimates were prepared to indicate the potential problem areas and appropriate corrective actions. These are discussed in greater detail in Section 3, (pages 3-9 through 3-16) of this report. These analyses resulted in a revised set of failure and repair rates and a time-phased scenario, which were exercised in the computer program and then compared with the baseline.

Task 6: Prepare Final Report

The effort and results of each task are presented in this final report. The fault trees, computer program, and failure and repair sources are provided in appendixes to this report. In addition to discussions of the implication of the analyses, underlying assumptions in conducting this project have been identified wherever they are appropriate to understand the approach, methods, or results.

PLANT DESIGN DESCRIPTION

The Heber Geothermal Demonstration Plant uses the binary cycle to generate electric power. Basically, the binary cycle uses two working fluids:

- The primary working fluid is the geothermal brine.

- The secondary working fluid is the hydrocarbon mixture of 80 percent isobutane and 20 percent isopentane.

The primary working fluid transfers its thermal energy to the secondary working fluid, which in turn serves to drive a turbine/generator set to produce electric power.

The plant can be divided into seven independent subsystems (ISSs), and their functions are linked to generate power from the geothermal brine. The ISSs and their functions are described in the following paragraphs. Figure 2-2 illustrates the partitioning of the plant for this project.

ISS1: Brine/Hydrocarbon Heat Exchangers

ISS1 is a series/parallel-connected train of two sets of four shell and tube heat exchangers. Each stage in the heat exchanger is directly connected to the succeeding stage to provide for a balanced flow, with no design provision for isolation or bypass of these stages. As shown in Figure 2-2, hot brine enters the fourth stage and leaves the first stage to be returned to the geothermal anomaly. The hydrocarbon working fluid enters the first stage and leaves the fourth stage to enter the turbine/generator set. Because of the design constraints, the failure of any single stage will fail 50 percent of the ISS. This failure also has the effect of reducing plant power output capacity by 50 percent.

It should be noted that because of temperature losses in the geothermal reservoir with time, an additional heat exchanger is planned for installation at approximately the midpoint of expected plant life to maintain net plant power output.
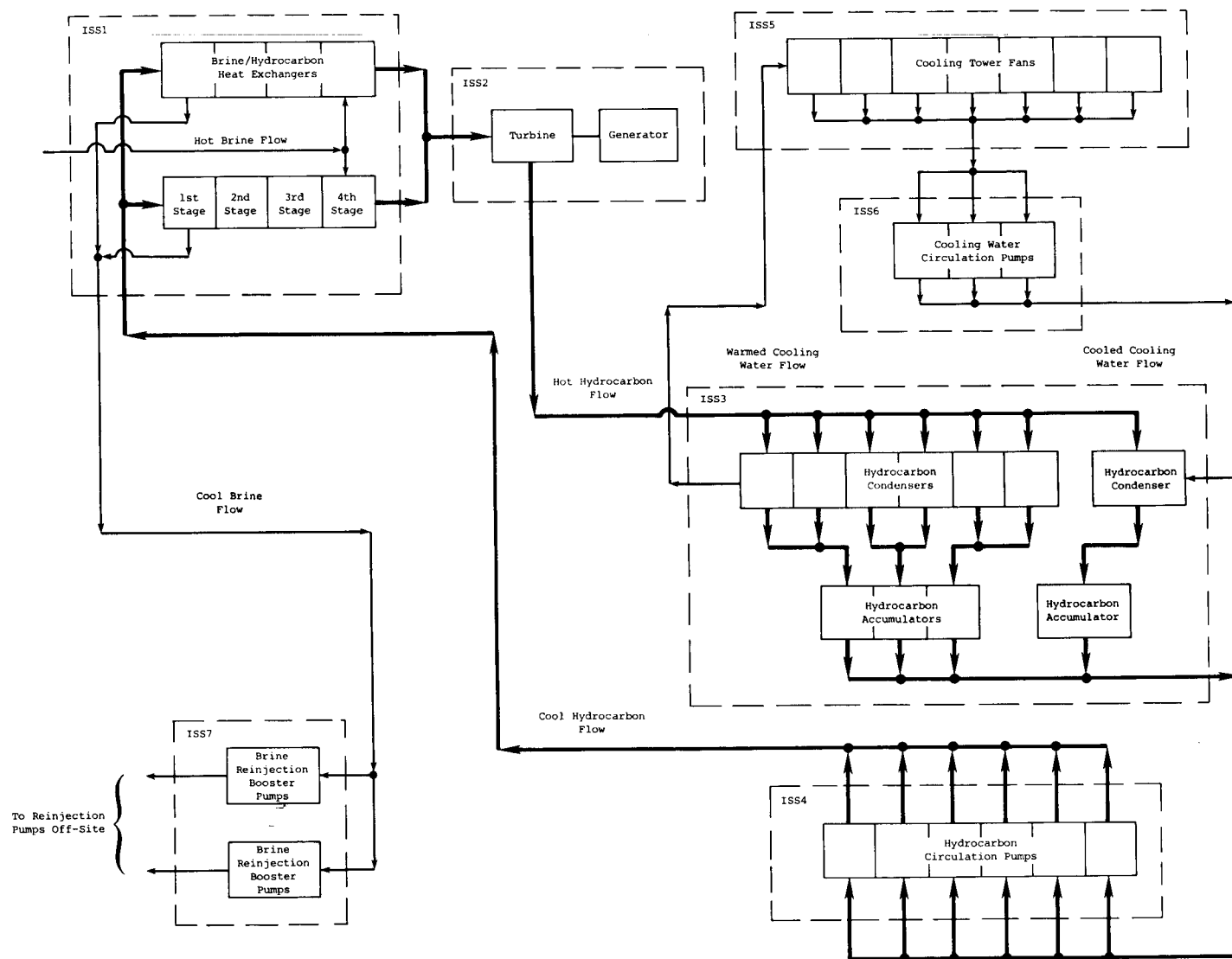
Figure 2-2. Heber Plant Partitioning

The impact of this change is not assessed herein, since it was not part of the baseline design.

ISS2: Turbine/Generator Set

A 65 MW_e turbine that expands the hot hydrocarbon vapors from the heat exchanger and produces a net output of 45 MW_e will be provided. The hydrocarbon vapors leave the turbine and are cooled through a set of condensers that are part of ISS3. A failure of either the turbine or the generator reduces plant power output to zero.

ISS3: Hydrocarbon Condensers and Accumulators

The hydrocarbon condensers and accumulators are arranged in three sets of two condensers and one accumulator and a fourth set of one condenser and one accumulator. Another condenser will be added to this last accumulator in the future when the geothermal anomaly undergoes thermal degradation, because more brine and hydrocarbon will be used to compensate for the temperature loss. At the direction of EPRI management, this additional condenser was included in the analysis.

The condensers receive the hot hydrocarbon vapors from the turbine exhaust; these vapors are cooled back to a liquid by passing over tubes that contain circulating cooling water. The accumulators function as containment vessels for the hydrocarbons, which are then piped to the hydrocarbon circulation pumps.

The valving and piping design of ISS3 is such that the failure of either a condenser or an accumulator removes the entire set from service. In this analysis, loss of a condenser and accumulator set reduced plant power by approximately 25 percent.

ISS4: Hydrocarbon Circulation Pumps

ISS4 is arranged in a parallel bank of six pump and motor combinations. The configuration provides for complete isolation of any one of the pumps in the ISS. The pump system is the primary source of flow for the working hydrocarbon fluid of the plant. Failure of either a motor or a pump removes that set from service with a corresponding power loss of approximately 16.6 percent. A seventh set is planned for future installation when the geothermal anomaly undergoes thermal degradation. This set is not included in the analysis.

2-10

ISS5: Cooling Tower Fan Modules

ISS5 consists of seven fan modules, each of which contains a fan and motor set. Cooling water is used in the hydrocarbon condensers (ISS3) and is pumped back to the cooling tower by the circulating water pumps (ISS6). The gravity flow through each of the seven modules is cooled by the fan pulling ambient air across the water cascade. Water is cooled below ambient air temperature, collected in the basin, treated, and pumped back to the system. The loss of any one of the modules, caused by the loss of either a fan or a motor, would result in a loss of approximately 14.3 percent cooling capability. As the anomaly degrades thermally, three additional modules will be installed to compensate for the increased hydrocarbon in the system required for thermal stability. These three modules were not addressed in the analysis.

ISS6: Circulating Water Pumps

ISS6 consists of three sets of pumps and motors, only two of which normally operate. The capacity of each is 50 percent of the total requirement. The third set is a normally inoperative spare. The loss of a single set, either pump or motor, has no effect on capacity; however, the loss of two sets reduces capacity by 50 percent. The loss of all three sets reduces output capacity to zero.

ISS7: Brine Reinjection Booster Pumps

The brine reinjection booster pumps are used for returning the cooled brine to the geothermal anomaly for reheating. The subsystem consists of two sets of pumps and motors. The geological pressures that exist in the anomaly will have a direct bearing on the size and capacity of these pumps. If a pump were to fail, the plant's capacity would be reduced by 50 percent, because of the inability to move the requisite amounts of heated brine through the plant.

FAULT TREES AND SYSTEM STATES

Fault trees are produced by an iterative process that should be used when a plant of any complexity is being analyzed. Structurally, each fault tree consists of a top-level event and a series of subsidiary events whose occurrence could produce the top-level event. Generally, these events can occur in two ways, defined by the use of either an AND gate, represented by ⌂, or an OR gate, represented by ⌂.

If an AND gate is present, all of the subsidiary events feeding into the gate must occur to bring about the top-level event. Thus, for example, if the failure of a particular pump can bring about the designated top-level event and if this pump is in parallel with another pump of the same type, size, and function, an AND gate

will be used to represent this configuration. The presence of an AND gate indicates that both the operating pump and the spare pump must fail before the top-level event can occur. If an OR gate is used in the tree, the occurrence of any of the events or the failure of any of the components directly connected to the gate will bring about the top-level event. These symbols, with their integration into simple trees, are illustrated in Figure 2-3. (Reference to a more detailed treatment of fault trees will indicate that there are many more fault-tree symbols than are shown here.) Although a more elaborate symbology could be required in some cases, the OR gate is the only relationship that was needed in analyzing the Heber configuration. That is, the failure of any one of the components in an ISS would cause a failure of that ISS. A complete set of fault trees for the Heber plant is presented in Appendix A. These trees were employed to write probabilistic expressions for failure and repair events for use in the model.
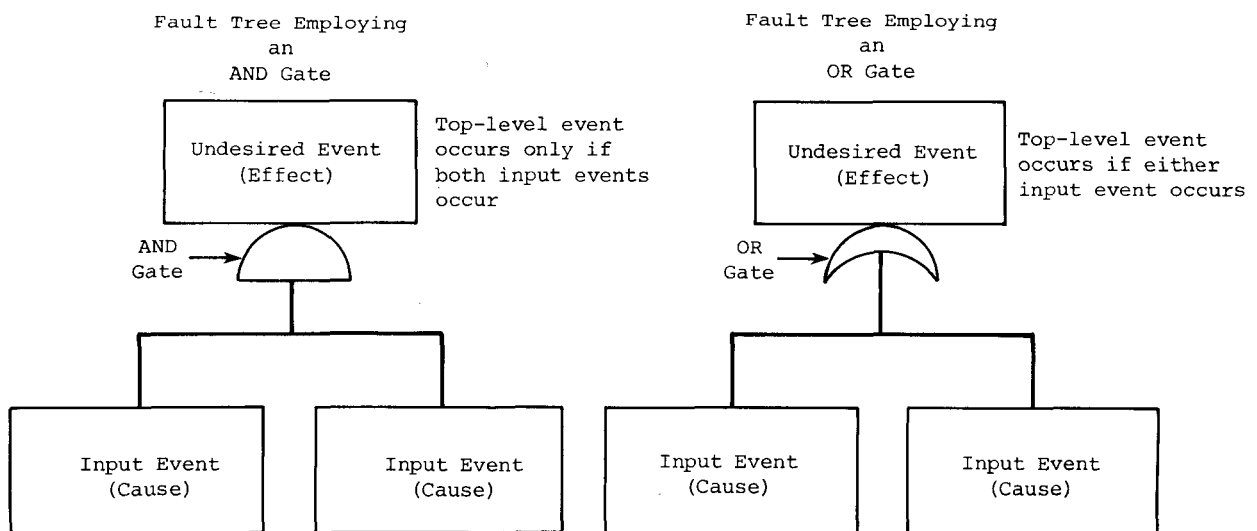
Figure 2-3. Examples of Fault-Tree Structures

The system capabilities were determined on the basis of the assumption that the output of each subsystem, or loss of output, was a linear relationship between capacity and the number of identical ISSs.* For example, the loss of a single hydrocarbon circulation pump (ISS4) would reduce the capability of the plant to handle the requisite amount of secondary working fluid by approximately one-sixth.

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*Letter from the Ben Holt Company to Mr. J. M. White, Jr., dated March 18, 1981, regarding linearity of plant capacity and failed ISS.

Twenty-five nonambiguous system states were defined for the Heber Plant; their asso-
ciated capacities are presented in Table 2-1. The numbers in parentheses in each
ISS column heading represent the quantity of similar subsystems present in each ISS
group. A zero in any column indicates that there are no failed subsystems in that
ISS in the given state (all operating). Any other number indicates the number of
failed subsystems of that ISS, which assists in defining the state of the entire
Heber plant. For example, in State 3, all subsystems of ISS1, ISS2, ISS3, and ISS7
are operating, while ISS4 has one failed subsystem and ISS5 and ISS6 are defined as
having less than two (<2), either zero or one, failed subsystems. The resulting
plant capacity in State 3 is 83 percent of the full rated output.

Table 2-1

HEBER SYSTEM-STATE DEFINITIONS

State	ISS1 (2)	ISS2 (1)	ISS3 (4)	ISS4 (6)	ISS5 (7)	ISS6 (2+1)	ISS7 (2)	Percentage of Maximum Capacity
1	0	0	0	0	0	<2	0	100
2	0	0	0	0	1	<2	0	86
3	0	0	0	1	<2	<2	0	83
4	0	0	1	<2	<2	<2	0	75
5	0	0	<2	<2	2	<2	0	72
6	0	0	<2	2	<3	<2	0	67
7	0	0	<2	<3	3	<2	0	58
8	1	0	<2	<3	<4	<2	0	50
9	<2	0	2	<3	<4	<2	0	50
10	<2	0	<3	3	<4	<2	0	50
11	<2	0	<3	<4	<4	2	0	50
12	<2	0	<3	<4	<4	<3	1	50
13	<2	0	<3	<4	4	<3	<2	43
14	<2	0	<3	4	<5	<3	<2	33
15	<2	0	<3	<5	5	<3	<2	29
16	<2	0	3	<5	<6	<3	<2	25
17	<2	0	<4	5	<6	<3	<2	17
18	<2	0	<4	<6	6	<3	<2	15
19	2	<2	<5	<7	<8	<4	<3	0
20	<2	1	<5	<7	<8	<4	<3	0
21	<2	0	4	<7	<8	<4	<3	0
22	<2	0	<4	6	<8	<4	<3	0
23	<2	0	<4	<6	7	<4	<3	0
24	<2	0	<4	<6	<7	3	<3	0
25	<2	0	<4	<6	<7	<3	2	0

ASSESSMENT MODEL DESCRIPTION

The Heber plant, like other advanced power-generation plants, is a reasonably complex system capable of operating over a number of states, ranging from full capacity to no capacity. To represent these conditions adequately in assessing plant reliability and availability, a system's effectiveness approach was employed. As mentioned earlier, this approach was initially developed and applied to a gasification-combined-cycle power plant. The following definitions were employed in the assessment of the Heber plant using this methodology:

- Reliability Measure. The expected* time for the plant to reach an a priori defined level of effectiveness in the absence of corrective maintenance, given that the plant was initially in a completely "up" condition. (For this analysis a 50 percent level of effectiveness was used.) This time represents a measure of the inherent reliability of the plant design.

- Availability Measure. The steady-state** effectiveness value when corrective maintenance is included.

- Effectiveness. The sum of the weighted contribution of each possible system state to the plant's output capacity. It can be expressed as an absolute (e.g., megawatts) or as a percentage of maximum capacity, and it represents an averaging over the possible system states or expected value for the plant. Further, since the likelihood of being in each particular state will vary with time, effectiveness will be a time-dependent quantity that will approach zero if repair is not permitted, and it will approach a finite steady-state value when repair is permitted.

The effectiveness function is determined by a Markov analysis and is defined for the interval $(t, t + \Delta)$ by the following matrix products:

$$E(t, t + \Delta) = A(t)T(t, t + \Delta t)C$$

where the matrices are defined as follows:

- $A(t)$ is a row matrix, called the availability matrix, whose elements $A_i(t)$ are the probabilities that the system is in each of its possible states at time t. If there are N_s possible states, then

$$\sum_{i=1}^{N_s} A_i(t) = 1$$

for all values of t. Initially, i.e., at t = 0, $A(0) = (1,0,...0)$ or in other words, the system is in an "all up" condition with zero probability of being in a state of degraded capability.

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*"Expected" is used with respect to an average value. Although no specific unit would operate in precisely this way, the average of all units should.

**Steady state is equivalent to the average over a long period of time.

- $T(t, t + \Delta t)$ is a square matrix ($N_s \times N_s$), called the transition matrix, whose elements (T_{ij}) are the probabilities of the system's transitioning from state i to state j during the interval ($t, t + \Delta t$). These probabilities are defined by the constituent subsystem reliability and maintainability probability expressions and the state definitions. The time interval, Δt, is made sufficiently small so that the probability of multiple events occurring during the interval is negligibly small. Further, when corrective maintenance is not permitted (i.e., for the reliability assessment), all elements of the transition matrix containing repair events are set to zero.

- C is a column matrix having N_s elements, called the capability matrix. Each element (C_i) represents the capacity of the plant when it is in state i. For the Heber analysis, the capacity of each state was expressed as a percentage of the maximum capacity.

Figure 2-4 is a flow diagram of the computer program employed in the analysis. Appendix C presents a detailed description and program listing.

Inputs to the program, which has been configured for use on a CDC time-share system, include component data entry and a set of responses to inquiries. The required responses are the type of run (reliability or availability), the time interval (in hours) between sets of calculations, and the number of iterations (complete time intervals) to be calculated.

A 12-hour time interval was selected for the Heber design, because it was estimated to be an interval in which the probability of more than one state change was very small. However, the interval was still large enough to preserve computer efficiency.

After the failure and repair parameters for each component in each ISS and the appropriate inquiry responses are entered, the program reads the data file and calculates each ISS reliability and maintainability measure from the component parameters and the fault tree logic. The availability and transition matrices are updated to account for state changes. Substate* availabilities are updated and the availability of each ISS is subsequently updated. Finally, the expected effectiveness of the entire plant is updated for each iteration of the program. Program results are then printed.

Printed results of the program are the effectiveness (or equivalent operational availability) of the plant for each of the intervals selected and the availability associated with each state in the last interval. The data may then be varied to test for sensitivity or criticality by selecting the additional run option.

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*This update is required for those states defined by an ISS entry having a "less than" number (e.g., <2) entry.
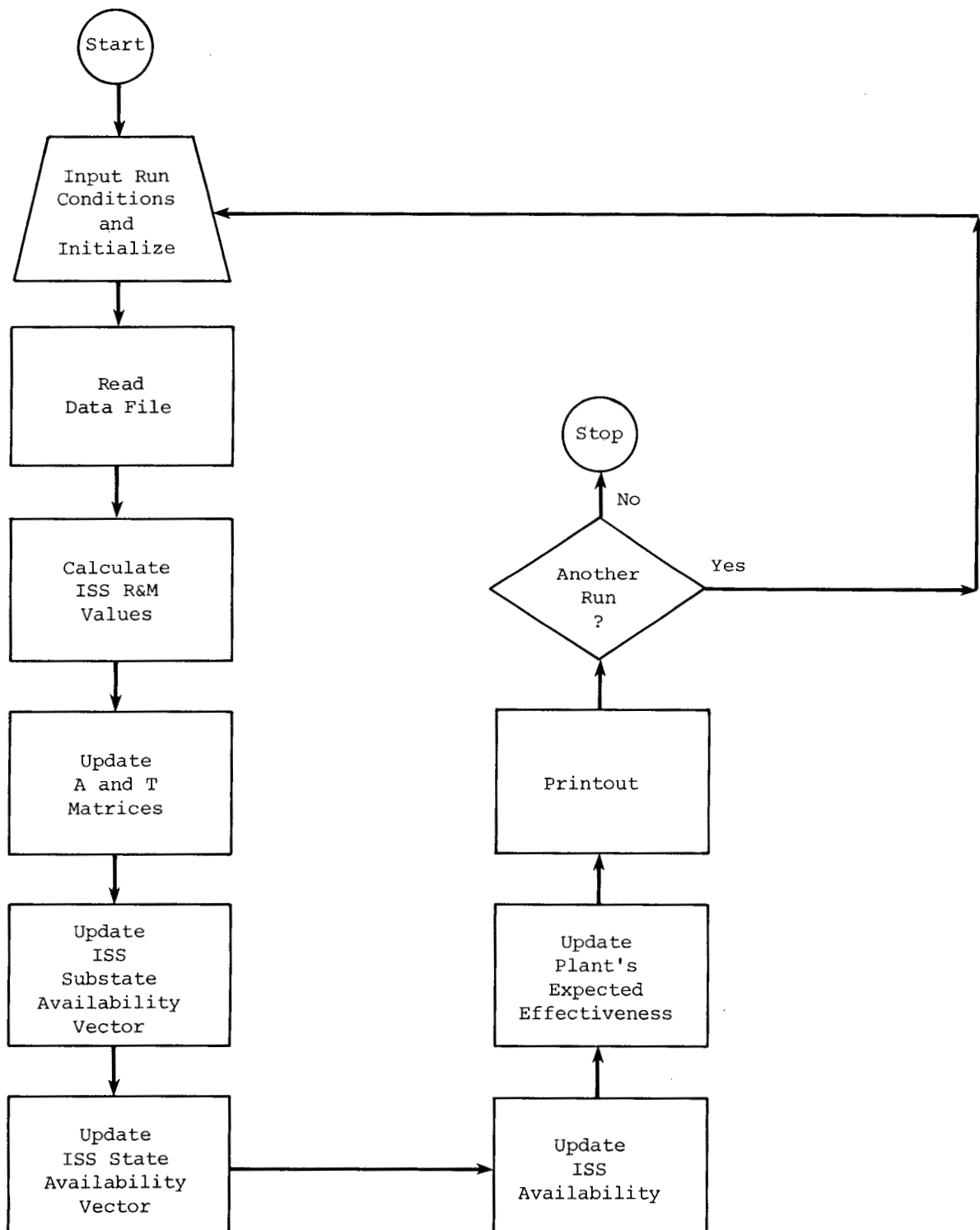
Figure 2-4. General Flow Diagram of the Heber Program

DATA BASE

The search for component and subsystem reliability, maintainability, and performance data required contacting numerous potential sources. The following industries and associations agreed to provide information for the study:

- Two electric power utilities

- Two petroleum refining companies

- Two bromine manufacturers

- Two electric power associations - the National Electric Reliability Council and the Edison Electric Institute

- A turbine manufacturer

- The architect-engineer responsible for the preliminary design of the Heber plant

Although other potential sources were contacted, data either were nonexistent or were not disclosed for proprietary reasons. Because of the lack of similar systems in service, the value of this proprietary data may be limited even if it were available. Data results are presented in Section 3. Appendix B lists the specific sources who provided information used in the study. Results of these efforts are discussed in the following paragraphs.

Electric Power Utilities

The two electric power utilities agreed to provide data on those components in cooling tower fan modules (ISS5) and circulating water pumps (ISS6). The utility personnel contacted included central engineering office representatives and site operations and maintenance personnel. In general, data for circulating water pumps and cooling tower fan modules were representative of the Heber design and were believed to be representative of industry experience.

Petroleum Refining Companies

Two petroleum refining companies provided operational information on turbines (ISS2), hydrocarbon condensers and accumulators (ISS3), and hydrocarbon circulation pumps (ISS4). The central engineering offices and two operating sites were contacted for their operation and maintenance experience with these equipments. Neither had experience with turbines of the size to be used at Heber, but they did offer opinions on similar designs believed to be representative of the larger unit. Hydrocarbon condensers and accumulators are standard refinery equipment and, with the correct choice of materials to match the type of service, perform satisfactorily

for a number of operating years. The hydrocarbon circulation pumps at Heber are 2,000 brake horsepower (bhp), whereas the largest that either of the two refineries had was 1,200 bhp. Their operating experience with this pump was excellent, and the refiners believed that 2,000 bhp should give nearly equivalent service with proper maintenance and steady-state operation. In their opinion, the data for the smaller unit could be extrapolated and applied to the larger units.

Bromine Manufacturers

Two bromine manufacturers were contacted for the operation and maintenance histories of their brine heat exchangers (ISS1), spent brine reinjection booster pumps (ISS7), and their associated components. The operating histories of heat exchangers, using hot brine as one of the working fluids, indicate that they are subject to frequent failures during operation. The users of the heat exchangers stated that the choice of materials used in fabrication is a critical factor. The size and capacity of the reinjection pumps is related to the "downhole" pressure of the anomaly; i.e., if the pressure is minimal, then smaller pumps can be used. Normal operating procedures require that the pumps run in a steady-state mode. Steady-state operation has produced acceptable performance histories for this industry. These data and the estimates were considered to be directly applicable to the Heber plant.

Electric Power Associations

Both the Edison Electric Institute (EEI) and the National Electric Reliability Council (NERC) were contacted for information on the operating histories of turbines and generators (ISS2) in the 65 MW output range. The NERC ten-year data on units of this size were reviewed for outage and repair histories. Both the failure and repair statistics were used in this project. This data base included 48 systems and 95 units, for a total of 458 unit-years.

Turbine Designer and Manufacturer

The designer and manufacturer of the axial flow design turbine, or hydrocarbon expander (part of ISS2), was requested to provide test, performance, and repair statistics on the design. No quantitative data were available; however, other information useful to this project was available, including estimates by the manufacturer that correlated well with the opinions of hydrocarbon expander experts at the petroleum refining companies.

Section 3

ANALYSIS RESULTS

This section presents the results of the analyses and investigations conducted for the Heber project. In addition to presenting the data base used in the analyses, this section describes the baseline assessment of the Heber Geothermal Demonstration Plant preliminary design and also the impact of reliability growth. The results of the preliminary design analysis, or baseline case, consist of reliability and availability assessments, a sensitivity analysis, and a ranking of the various components on the basis of their impact on overall plant performance. Details of these results are presented in the following paragraphs.

DATA BASE

The component failure and repair data base for the Heber Geothermal Demonstration Binary Plant was assembled with the cooperation of the organizations listed in Appendix B, subject to the constraints discussed in Section 2. However, a number of problems were encountered in developing this data base, primarily because of the virtual nonexistence of histories on like components. A limited quantity of data were available on similar equipments (e.g., for different sizes or capacities of equipment or equipment operating in a different environment). These data were extrapolated* to conform to the physical, operational, and environmental requirements of the Heber design. Data available for use were at a higher level of indenture than either planned or desirable. An examination of the fault trees in Appendix A indicates the desired level for component data. However, data used, or data capable of being estimated by knowledgeable sources, were at a higher component level. Finally, many of the sources contacted either did not collect this type of information or, if they did, would not release it for proprietary reasons.

Data used in the analysis are presented in Table 3-1. Table 3-2 lists the environmental conditions under which the data are applied. In examining this data base, it should be noted that only ISS2, ISS5, and ISS6 are based on histories of like components. The remaining component data were derived from a combination of extrapolations of similar equipment data and data estimates of knowledgeable

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*The method used to extrapolate data was based on best estimates obtained from discussions with knowledgeable designers and users of the equipment.

Table 3-1

FAILURE AND REPAIR DATA

ISS	Subsystem or Component	Components		Subsystem	
		MTBF (Hours)	MTTR (Hours)	MTBF (Hours)	MTTR (Hours)
1	Brine/Hydrocarbon Heat Exchangers			1,980	168
2	Turbine/Generator			16,545	307
	Turbine	25,820	370	--	--
	Generator	46,445	193	--	--
3	Hydrocarbon Condensers/ Accumulators			19,147	316
	Condenser	43,560	366	--	--
	Accumulator	158,400	168	--	--
4	Hydrocarbon Circulation Pumps			6,592	168
	Pump	7,920	168	--	--
	Motor	39,300	168	--	--
5	Cooling Tower Fan Modules			7,011	710
	Fan	15,840	1,512	--	--
	Motor	12,575	72	--	--
6	Circulating Water Pumps			210,900	57
	Pump	1,265,398	100	--	--
	Motor	253,080	48	--	--
7	Brine Reinjection Booster Pumps			9,900	48

personnel. Independent subsystem data were calculated by using the combined availabilities of components to determine their measures of reliability and maintainability.

PRELIMINARY DESIGN (BASELINE) ASSESSMENT

The following paragraphs present the results of the baseline assessment, including an assessment of the reliability and availability of the preliminary design, an

Table 3-2

ENVIRONMENTAL STRESS DATA

ISS	Subsystem or Component	Environmental Conditions	
		Design Data	Operating Data
1	Brine/Hydrocarbon Heat Exchangers		
	Tube (Brine) Side	360°F, 180 psig	109°-295°F, 138 psig
	Shell (Hydrocarbon) Side	360°F, 67 psig	360°-153°F, 535 psig
2	Turbine/Generator		
	Turbine	360°F, 650 psia	295°F, 500 psia
	Generator	13,800 Vac	--
3	Hydrocarbon Condenser/ Accumulator		
	Condenser		
	Shell	450°F, 165 psig	104°-166°F, 58 psig
	Tube	450°F, 100 psig	90°-108°F, 30 psig
	Accumulator	450°F, 165 psig	104°F, 56 psig
4	Hydrocarbon Circulation Pumps		
	Pump	104°F, 4,707 gpm	104°F, 4,707 gpm
	Motor	1,800 rpm, 2,000 hp	--
5	Cooling Tower Fan Modules	95°F, 140,000 gpm	90°-108.7°F, 137,085 gpm
6	Circulating Water Pumps		
	Pump	90°F, 68,543 gpm	--
	Motor	585 rpm, 2,000 hp	--
7	Brine Reinjection Booster Pump	--	160°F, 300 psig

analysis of the sensitivity of the availability assessment to uncertainties in the data, and an analysis of the criticality of major components to the performance of the plant.

Reliability Assessment

The analysis model was exercised for a total of 200 iterations (12-hour periods), or 100 days, to assess the inherent operating reliability of the plant. In this type of analysis, the plant is assumed to start operating in an "all up" condition and is permitted to run while failures occur in accordance with the parametric failure rates identified. However, repairs are inhibited so that no corrective (or planned) maintenance is permitted. The run is terminated when the plant decays from 100 percent expected capacity to 50 percent of that capacity. The 50 percent limit is chosen arbitrarily and has no resemblance to real operations. This type of analysis does, however, provide an insight into the reliability of the components in the plant and provides a measure of the plant's inherent reliability. The time for the Heber plant to decay to the 50 percent level was approximately 37.5 days (75 twelve-hour intervals). This value may be compared with that of a previously analyzed coal gasification-combined-cycle (GCC) power plant and a large coal combustion power plant; their inherent reliability values were nine days and eight days, respectively. A comparison of the Heber plant and the theoretical GCC plant (identified as EXTC) is illustrated in Figure 3-1. The comparison shows that the inherent reliability of components in the Heber design may be as much as four times more reliable than those selected for the EXTC GCC power plant.

Availability Assessment

The availability assessment approach differs from that for the inherent reliability in that repairs are permitted, thereby enabling the plant to have both upward and downward state transitions. In this analysis, the computer program runs through a series of iterations until the plant performance decays to its steady limit, i.e., the point at which failures and repairs reach virtual equilibrium. The baseline case steady-state effectiveness closely approximates an equivalent operating availability for the plant.* The steady-state effectiveness for the plant was calculated to be 80.5 percent and is shown in Figure 3-2. This value was reached at approximately 2,136 hours, or 89 days.

The reliability assessment results are also shown for comparison. The coal-fired plant corresponding availability values were 81.6 percent and the EXTC GCC plant was 79.4 percent. The steady-state availabilities for each of the defined system states are presented in Table 3-3. It can be seen from the table that the most likely state is the "all up" state (State 1), with an availability of 34.2 percent.

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*If scheduled maintenance were included in the analysis, then the steady-state effectiveness would be analogous to the NERC definition of equivalent availability.
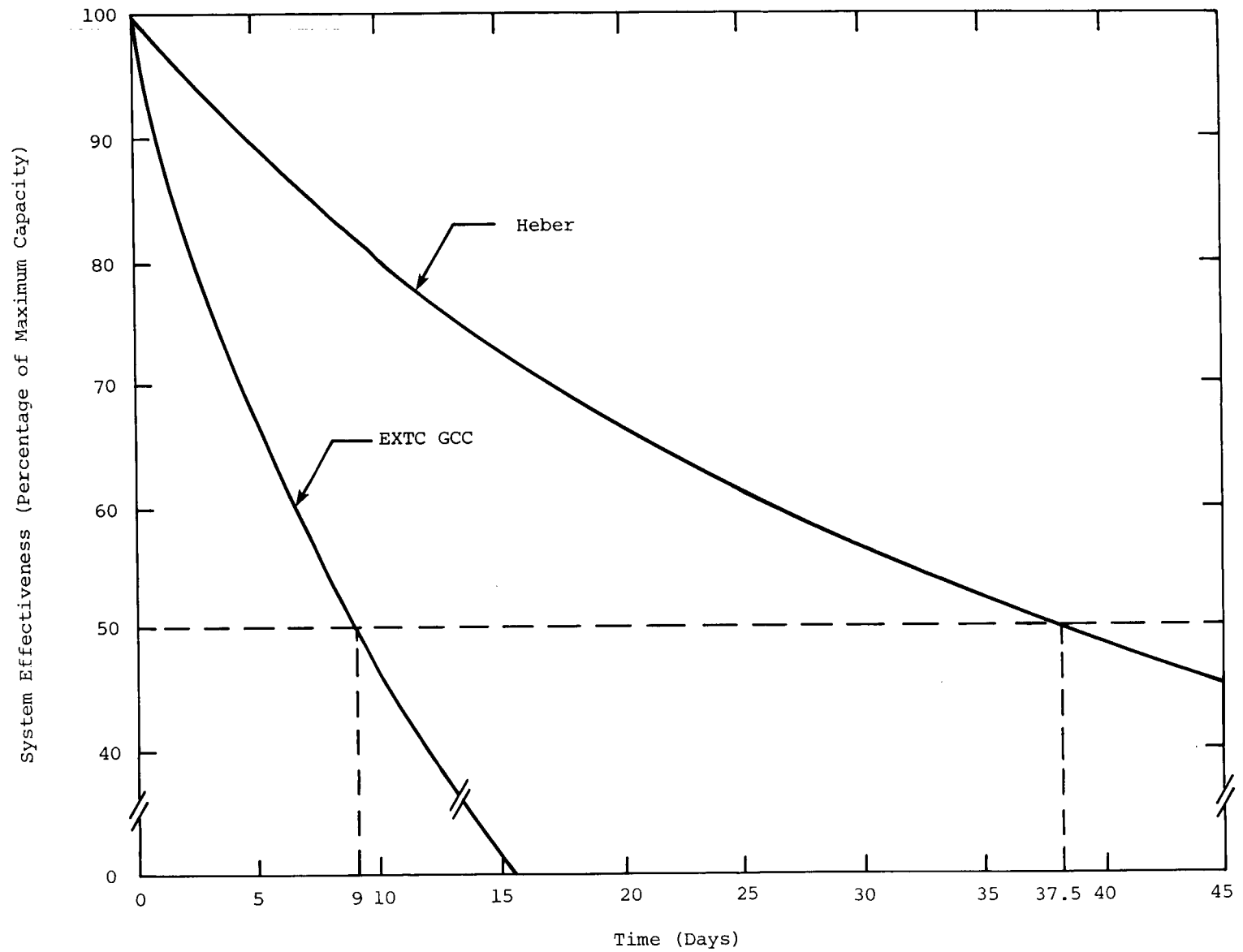
Figure 3-1. A Comparison of Inherent Reliability (Effectiveness) vs. Time for the Heber Plant and EXTC GCC Plant
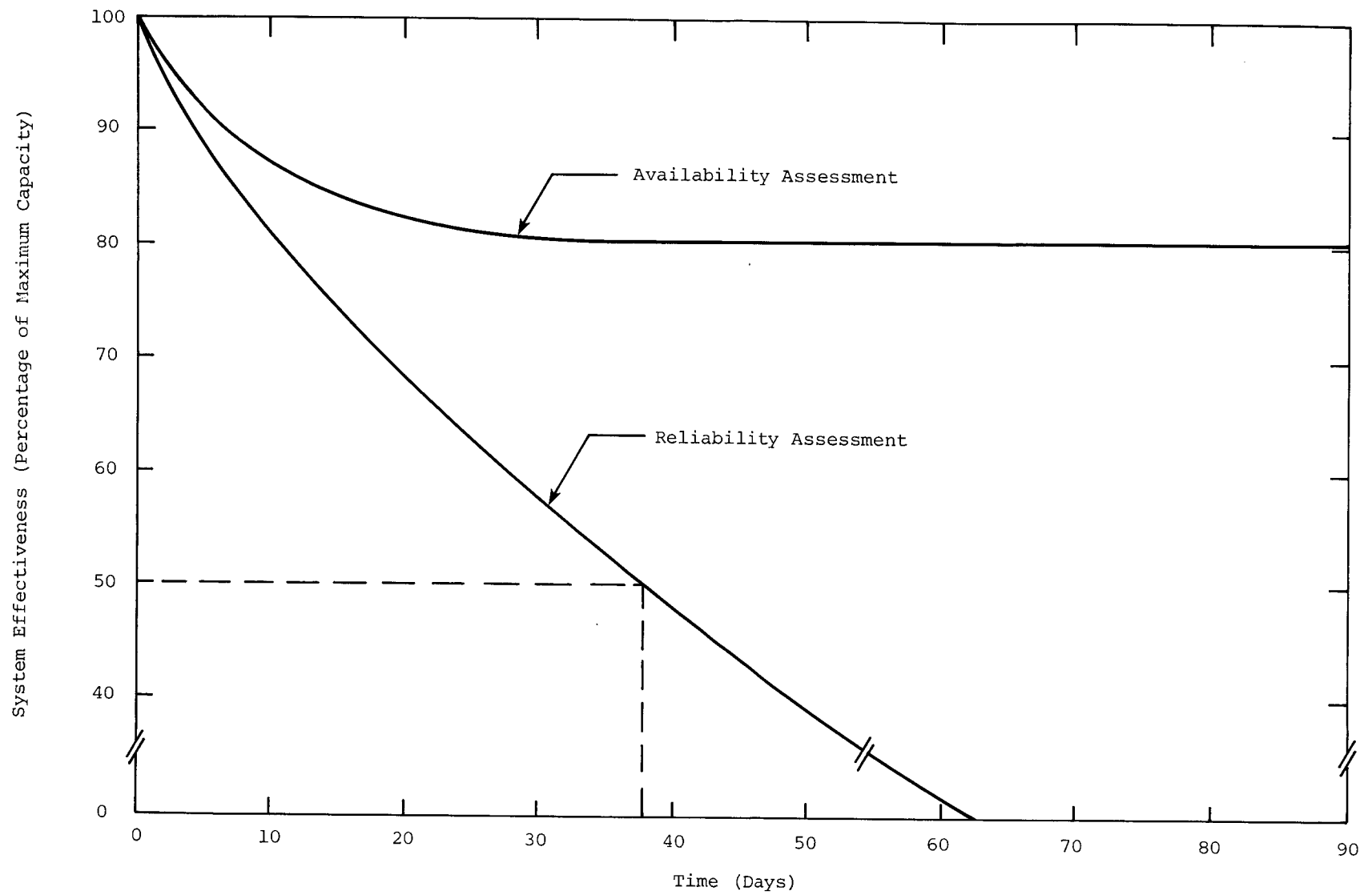
Figure 3-2. Heber Baseline Reliability and Availability Assessment Results

Table 3-3

SUMMARY OF STEADY-STATE
AVAILABILITIES

State	Percentage of Capacity	Percentage of Availability
1	100	34.2
2	86	23.7
3	83	8.6
4	75	4.5
5	72	8.7
6	67	0.6
7	58	1.4
8	50	14.4
9	50	0.1
10	50	<0.1
11	50	<0.1
12	50	1.0
13	43	0.2
14	33	<0.1
15	29	<0.1
16	25	<0.1
17	17	<0.1
18	15	<0.1
19	0	0.6
20	0	1.8
21	0	<0.1
22	0	<0.1
23	0	<0.1
24	0	<0.1
25	0	<0.1

Further, it can be seen that the probability of at least 75 percent capacity (the sum of availabilities for states having 75 percent capacity and above) is 71 percent and that the probability of a full outage (zero capacity) is approximately 2.5 percent. Finally, it was determined from the baseline assessment results that the probability of 100 percent capacity for five days was 0.885 and the probability of at least 75 percent capacity for 60 days was 0.725.

Sensitivity Analyses and Component Rankings

Sensitivity analyses were performed to determine the impact of uncertainties in the data base on baseline results. The impact on steady-state effectiveness is compared with variations in the availability of each of the major subsystems. The ISS

availabilities were varied, as shown in Figure 3-3, to demonstrate the effects of un-
certainties in the component data. The figure indicates that the dominant subsystem
is the brine/hydrocarbon heat exchanger (ISS1) by a narrow margin, with turbine/gen-
erator (ISS2) and cooling tower fan modules (ISS5) closely following. The shallow
slopes of the remaining subsystems indicate relative insensitivity to data uncertain-
ties, because of their limited effect on baseline steady-state availability.

In assessing the sensitivity to data uncertainties, Figure 3-3 illustrates that a
change in the availability of the cooling tower fan modules (ISS5) from the baseline
90 percent to a hypothetical 80 percent, for example, could decrease the steady-state
effectiveness measure to approximately 0.73. It is unlikely that data are that in-
accurate, since such a change could be produced only by a large reduction in MTBF, an
even larger increase in MTTR, or both.
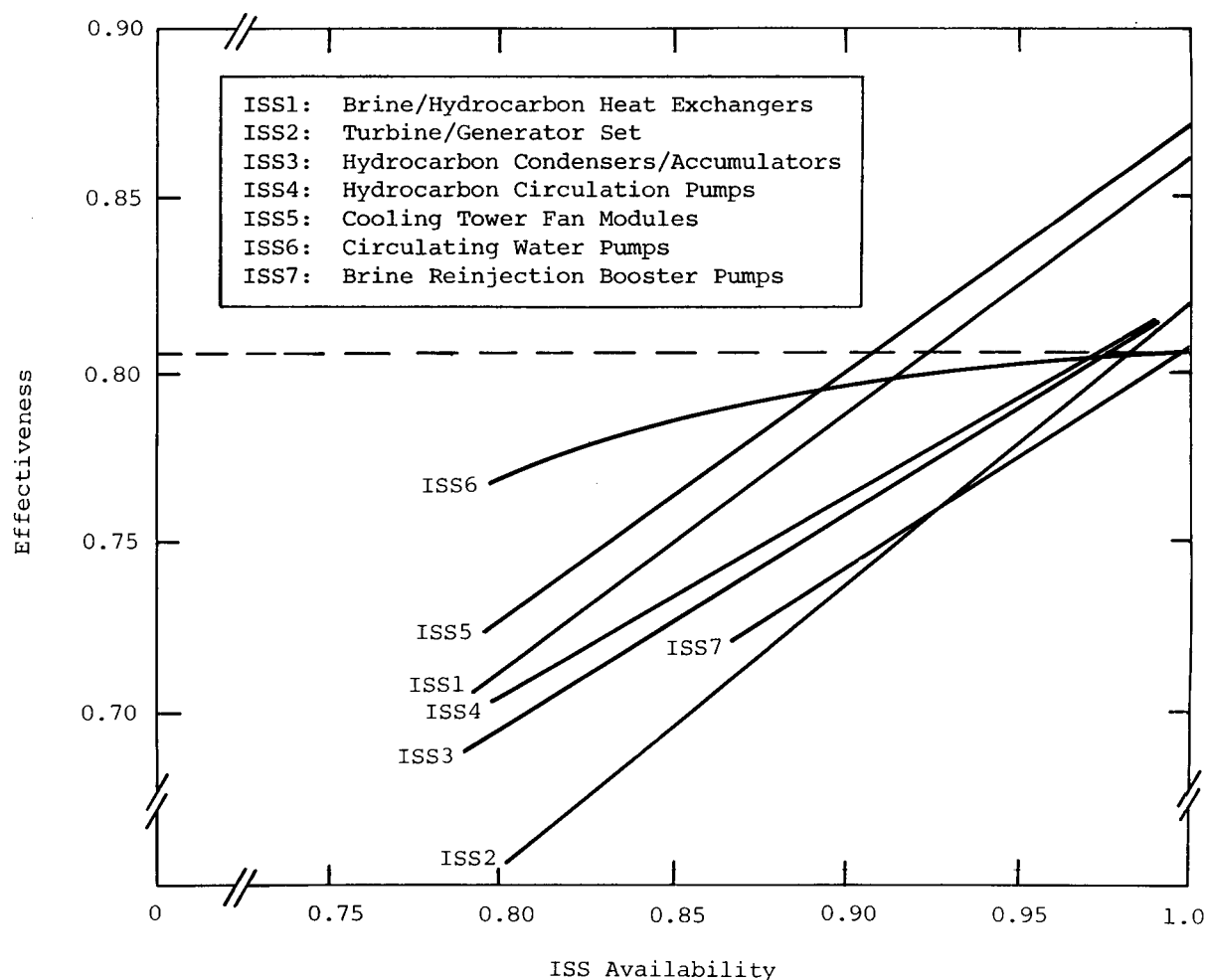
Figure 3-3. Subsystem Sensitivity Analysis

Component rankings were then developed in accordance with the following criteria:

- Power Lost - the increase in steady-state effectiveness when a component is made perfect.

- Availability - the change in steady-state effectiveness per change in component availability.

- Failure Rate - the change in steady-state effectiveness per change in component failure rate.

- Mean Time to Restore - the change in steady-state effectiveness per change in component mean time to restore.

The expressions used to determine the ranking scores* are presented in Appendix D. The resultant rankings are shown in Table 3-4. The table shows that the brine/hydrocarbon heat exchanger represents the most sensitive component, whereas the circulating water pump and motor have a comparatively negligible impact. In terms of their contribution to power lost, the heat exchanger and cooling tower fan modules are the most sensitive, while the turbine/generator is a more distant third.

Improvements in component availability indicate that the turbine/generator and the heat exchanger, in that order, followed closely by the cooling tower fan modules, are the most sensitive. The cooling tower fan is the component most sensitive to an improvement in failure rate, followed by the turbine, hydrocarbon condenser, and generator, in that order. In terms of improvements in repair and restore times, the heat exchanger is most sensitive, followed by the brine reinjection booster pump and the hydrocarbon circulating pump.

It seems clear from these rankings that efforts for system improvement, if economically feasible, should be concentrated on reducing the restore time or increasing the MTBF of the heat exchanger and the cooling tower fan modules, to achieve the most improvement from an availability standpoint. Since economics have not been included in this analysis, capital investment limitations may indicate other actions could be more cost-effective.

RELIABILITY GROWTH

As part of the baseline data-collection effort, potential areas of reliability improvement were investigated, and, where possible, source estimates of expected growth were obtained. Table 3-5 summarizes the identified potential improvements,

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*The score is the numeric result of calculating performance and is a relative number used to demonstrate ranking and the relative magnitude of differences between each ISS.

Table 3-4

HEBER COMPONENT RANKINGS

Component	Ranking by Criterion							
	Power Lost		Component Availability		Component Failure Rate		Component Mean Time to Restore	
	Score	Rank	Score	Rank	Score	Rank	Score	Rank
Brine/Hydrocarbon Heat Exchangers	5.92	1	76.7	3	10,948	5	0.03291	1
Turbine	1.16	3	81.7	1	29,381	2	0.00308	6
Generator	0.34	7	80.9	2	15,485	4	0.00173	7
Hydrocarbon Circulating Pump	0.97	4	48.4	9	7,797	8	0.00586	3
Hydrocarbon Circulating Motor	0.20	9	47.6	10	7,929	7	0.00120	8
Cooling Tower Fan	5.86	2	69.7	4	87,824	1	0.00367	5
Cooling Tower Motor	0.36	6	64.1	6	4,563	9	0.00504	4
Circulating Water Pump	0	12	1.0	12	100	11	0	12
Circulating Water Motor	0	11	1.0	11	48	12	0	11
Brine Reinjection Booster Pump	0.31	8	64.5	5	3,066	10	0.00645	2
Hydrocarbon Condenser	0.39	5	51.8	7	18,645	3	0.00117	9
Hydrocarbon Accumulator	0.05	10	51.5	8	8,633	6	0.00032	10

an estimate of timing relative to the initial plant operation date, and an estimate of the improved MTBFs.

Scenario for Reliability Growth

The scenario for potential reliability growth for each component in Table 3-5 is described in the following paragraphs. The effect on system availability of each individual subsystem change and the cumulative effects are shown in Table 3-6.

Brine/Hydrocarbon Heat Exchangers (ISS1). Although the carbon steel tubes in the heat exchangers have been tested in contact with the Heber anomaly brine with good

Table 3-5

POTENTIAL RELIABILITY IMPROVEMENT CANDIDATES

Component	ISS Baseline MTBF (Hours)	Estimated Improved MTBF (Hours)	Improvement	Assumed Timing
Brine/Hydrocarbon Heat Exchangers	1,980	7,920	Change tubing materials to titanium	5th year of operation
Hydrocarbon Condensers/ Accumulators	19,147	34,165	Change tubing materials to a copper-based alloy	5th to 7th year
Hydrocarbon Circulation Pumps	6,592	11,290	Change to oil mist system	3rd to 7th year
Cooling Tower Fans	7,011	14,020	Change fan blading materials	3rd to 7th year
Circulating Water Pump Motors	210,900	361,545	Manufacturer's estimated reliability growth	5th to 10th year
Brine Reinjection Booster Pumps	9,900	19,800	Manufacturer's estimated reliability growth	3rd to 7th year

results, knowledgeable personnel indicate that fouling and corrosion will cause eventual severe degradation to the brine loop. This corrosion rate will not be uniformly distributed in the tubing and will be intermittent with each shutdown and subsequent descaling operation. The problem is believed to be spot oxidation, resulting from admitting air into the system during planned maintenance operations. Corrosion of the steel tubes will be more rapid in some areas, thereby producing localized penetration of the tubes during operation. Plant availability will degrade as a direct result of these failures. Since there are no known satisfactory methods for preventing air from entering the system or for completely purging it, this type of failure will continue to present a reliability problem and could necessitate design changes.

A potential improvement would be to upgrade tube metallurgy by replacing the carbon steel tubes with more expensive titanium tubes. It is estimated that this change will result in a 400 percent improvement in heat exchanger MTBF, from 1,980 hours to 7,920 hours. The titanium tubes will permit operation of the heat exchangers for a full year without a shutdown for descaling and will also be impervious to Heber brine conditions. Since the change is a major construction effort, it is assumed to occur

Table 3-6

ESTIMATED CHANGES IN SUBSYSTEM AVAILABILITY AND
PLANT EFFECTIVENESS ATTRIBUTED TO RELIABILITY GROWTH

ISS	Subsystem or Component	Baseline		Improved		Net Change for Plant (Percentage Points)
		ISS Availability	Plant Effectiveness	ISS Availability	Plant Effectiveness	
1	Brine/Hydrocarbon Heat Exchangers	.92179	80.5%	.97923	84.9%	4.4
2	Turbine/Generator	.98178	80.5%	No Change Forecast		---
3	Hydrocarbon Condensers/ Accumulators	.98376	80.5%	.99804	81.3%	0.8
4	Hydrocarbon Circulation Pumps	.97515	80.5%	.98533	81.0%	0.5
5	Cooling Tower Fan Modules	.90804	80.5%	.95180	83.6%	3.1
6	Circulating Water Pumps	.99973	80.5%	.99984	80.6%	0.1
7	Brine Reinjection Booster Pumps	.99517	80.5%	.99758	80.7%	0.2
	Total Plant		80.5%		89.7%	9.2

in the fifth year of operation, at which time it is estimated that major overhauls of the heat exchangers would be scheduled. The effect on plant availability as a result of this change is an increase of 4.4 percent.

Hydrocarbon Condensers/Accumulators (ISS3). Irrigation water from the last section of the Imperial Valley system will be the cooling water used in the Heber plant. Despite treatment measures that may be attempted, the quality of this cooling water will degrade from its present level because of the harsh chemicals in the water. Therefore, an increasing number of failures and a more rapid rate of scaling of the carbon steel tubes are expected to occur, resulting in reduced heat transfer rates. Plant output would be degraded, because the condensers can neither be cleaned on line nor isolated, thereby requiring the shutdown of an entire condenser/accumulator stage.

It was assumed in this analysis that the operating utility would begin to retube these condensers during annual outages in the fifth year of operation and continue

into the seventh year. The choice of tubing for reliability growth would be a copper-based alloy such as Admiralty brass or copper-nickel. These alloys are resistant to the chemical composition of the irrigation water in terms of scaling and tube wall perforations from corrosion. It is predicted that a change to the new alloy would result in reducing the number of tube-wall failures and would extend the time between descaling operations to an annual outage task instead of several times per year. The resultant increase in MTBF is estimated at 34,165 hours, compared with the baseline estimate of 19,147 hours. The effect on plant availability as a result of this change is an increase of 0.8 percent.

Hydrocarbon Circulation Pumps (ISS4). Despite their large size (2,000 bhp), the hydrocarbon circulation pumps are designed using a sleeve-type bearing and pressurized lubrication system. In large pumps, it has been demonstrated that the oil mist system developed recently is more effective than the sleeve bearing system. Both users and designers of similar pumps are predicting an increase in MTBF of 100 percent by using the oil mist design. Since these pumps are critical to plant power lost and are sensitive to changes in restore time from the component-ranking analyses, it is assumed that the operating utility would desire to improve their overall availability in time. Since the pumps are large and costly, a gradual replacement was assumed to take place from the third to the seventh year of operation. Doubling the MTBF of the pump would result in an increase of the subsystem MTBF from 6,592 to 11,290 hours, with a subsequent improvement in plant availability. The effect on plant availability as a result of this change is an increase of 0.5 percent.

Cooling Tower Fan Modules (ISS5). Manufacturers of the fan and motor components anticipate and are planning for reliability improvements. Service life of both components is expected to double by improving fan blade materials, which will result in reduced stress on the motors. Better motor lubrication systems are also planned. These materials will be available when the first components start to fail, in approximately 1.5 to 2 years' time. To improve overall plant availability, it is assumed that the operating utility would repair and replace blades and motors during the third to the seventh year for a complete changeover. The ISS MTBF would increase from 7,011 to 14,020 hours with these improvements. The affect on plant availability as a result of this change is an increase of 3.1 percent.

Circulating Water Pumps (ISS6). The components of ISS6 are highly reliable; however, the large motor MTBF is approximately four times lower than that of the pump. Pump motor manufacuters anticipate improvements in both the bearing and lubrication

system designs, which should result in doubling the service life of the motor. It is assumed that because of the high cost of these items, changeover would be more likely to occur between five and ten years from start up, or when the motors require major overhaul. The resulting improvement in the ISS6 MTBF would increase from 210,900 hours to 361,844 hours. The effect on plant availaiblity as a result of this change is an increase of 0.1 percent.

Brine Reinjection Booster Pumps (ISS7). These pumps are still in the early development stage. As additional moderate temperature geothermal anomalies are used for power generation, designers believe that their early experience will result in at least a 200 percent improvement in service life. These evolutionary changes will improve MTBF from 9,900 to 19,800 hours at the subsystem level and are assumed to take place during the third and seventh year of operation. The effect on plant availability as a result of this change is an increase of 0.2 percent.

Assessing the Impact of Reliability Growth

The scenario for implementing reliability growth is illustrated in Figure 3-4. The figure depicts growth beginning gradually in the third year of operation and continuing through the tenth year. The resulting impact on plant availability over this period is a growth of slightly more than 9 percent, as shown in Table 3-6. No growth is forecast for the turbine/generator (ISS2), on the basis of the manufacturer's projections of limited growth potential.

In Table 3-6 improvements in plant availability were first calculated individually by changing each subsystem in turn, while holding the remaining subsystems at baseline values. In addition, it is believed that further growth could be achieved by introducing bypass capabilities in the heat exchanger and condenser/accumulator subsystems. This, for example, would permit operation of the plant in additional higher-capacity states when a failure occurs in a heat exchanger rather than losing the entire subsystem and dropping to 50 percent capacity. Figure 3-5 presents an approximation of the cumulative reliability growth scenario, using the information depicted by individual subsystem in Figure 3-4.
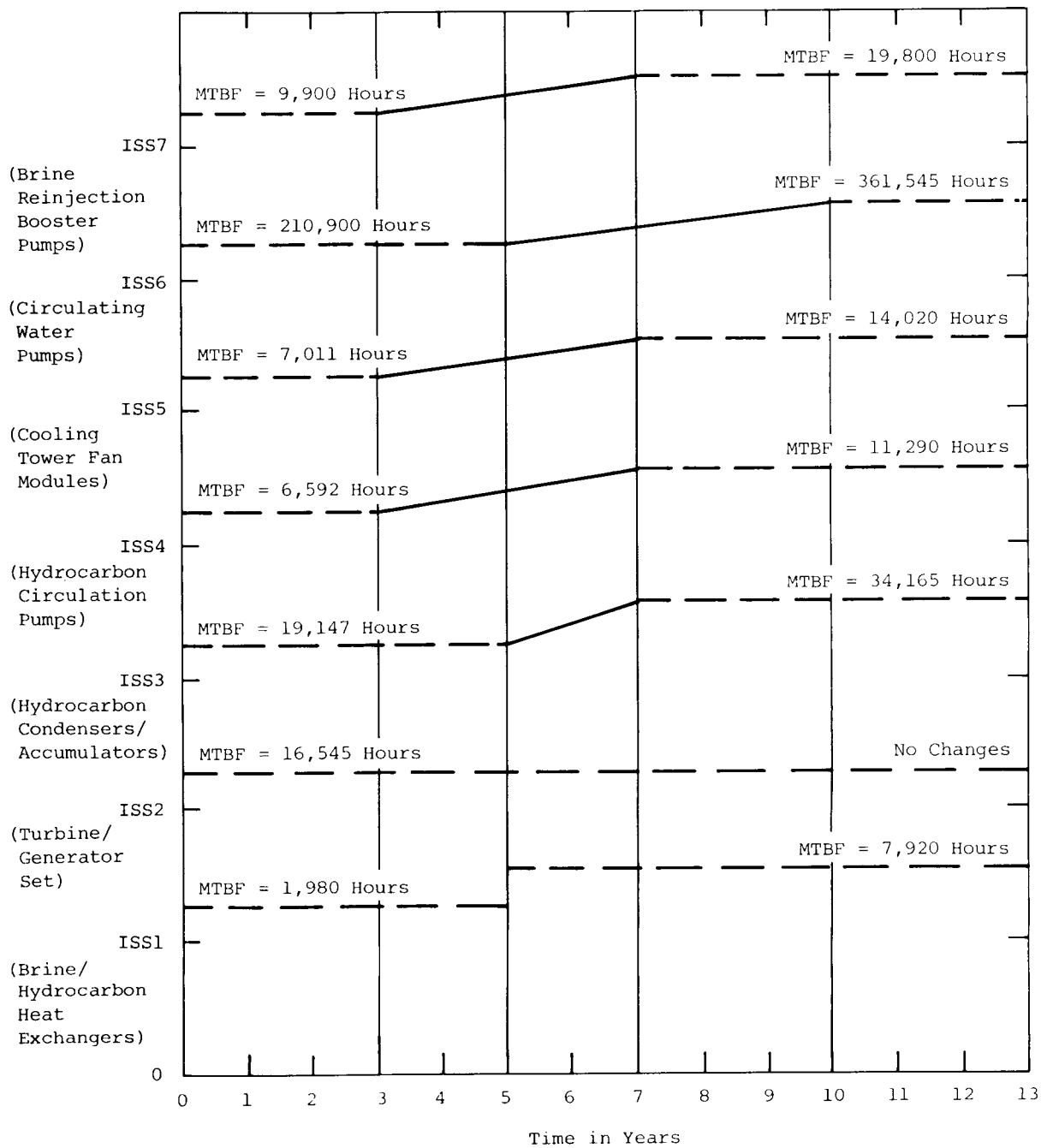
Figure 3-4. Reliability Growth Scenario
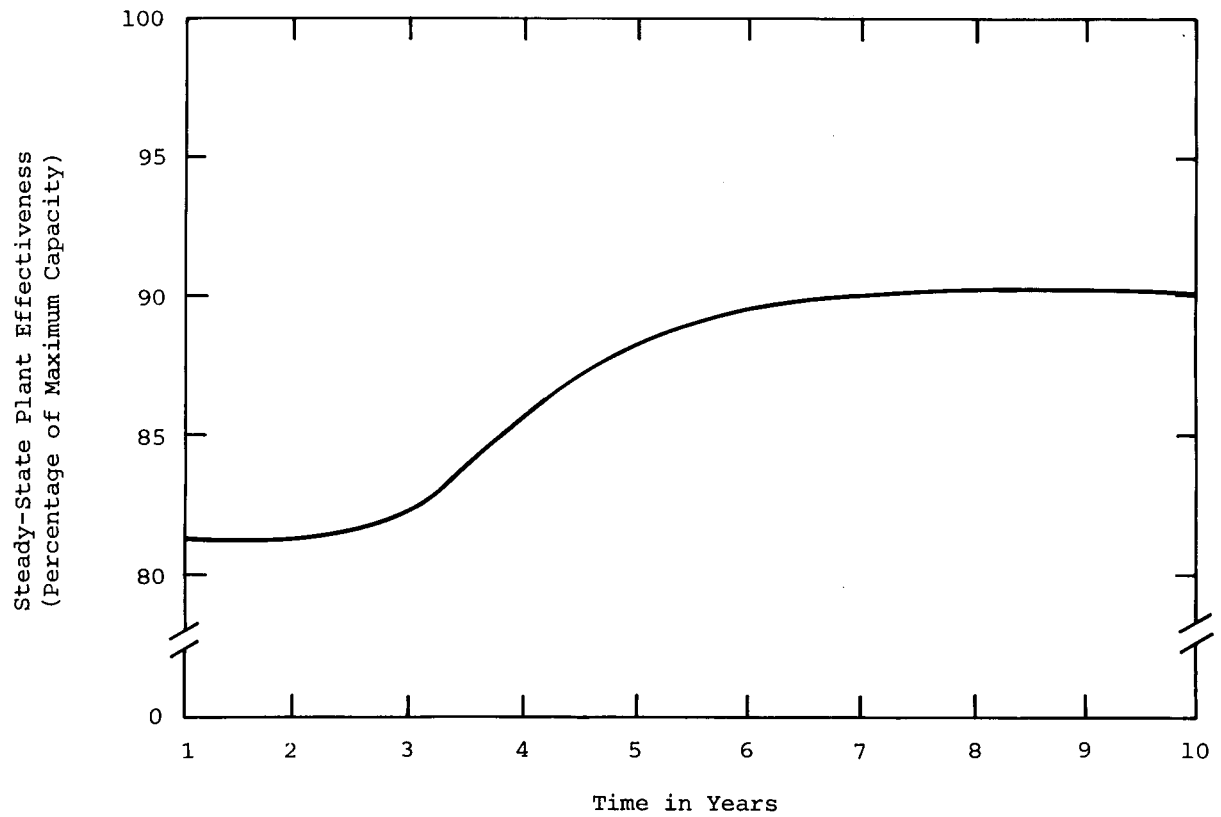
Figure 3-5. Cumulative Effects of Reliability Growth on
Steady-State Effectiveness

Section 4

CONCLUSIONS AND RECOMMENDATIONS

This section presents the conclusions derived from the evaluation of the Heber Geothermal Demonstration Plant preliminary design and an assessment of areas of potential reliability improvement. Recommendations for future courses of action, on the basis of the results and conclusions, are also provided.

CONCLUSIONS

In response to the primary objectives of the study, the following general conclusions are presented:

- A geothermal component data base was developed that was sufficient for the initial analysis. The data base should be expanded to provide for improved assessment capability.

- Both a reliability and an availability assessment of the preliminary Heber design was performed, resulting in an inherent reliability of 37.5 days to degrade to 50 percent capacity under no repair conditions and a steady-state availability of 80.5 percent with full maintenance and repair.

- The most critical components in the Heber plant preliminary design are the brine/hydrocarbon heat exchangers (ISS1), with a low MTBF of 1,980 hours. The second most critical are the cooling tower fan modules (ISS5), with a large MTTR of 1,512 hours.

- The sensitivity analyses disclosed that the heat exchangers (ISS1), cooling tower fan modules (ISS5), and turbine/generator (ISS2) are most sensitive to data uncertainties. These results compare favorably with the criticality rankings.

- Changes to the design to enhance plant availability were investigated. Several specific design change recommendations were developed, and further potential areas of design and technology improvement areas were identified.

- The impact of reliability growth on the Heber plant was assessed and a scenario developed to upgrade performance over a seven-year period, beginning with the third year and concluding with the tenth year of operation. The resulting improvement should increase (by 9.2 percent) steady-state availability to 89.7 percent.

- The analysis of the preliminary design shows an 88.5 percent probability of running at 100 percent of rated output for five days. The probability that it can produce at least 75 percent of rated output for 60 days is 72.5 percent.

- Evaluation of the Heber design, using the baseline data, produced reliability and availability estimates that were equal to or better than previously evaluated gasification-combined-cycle (GCC) and coal-fired plant (CFP) designs. The plant is considered to be more inherently reliable than either of the other advanced technology designs, and the steady-state availability falls between the slightly higher CFP design and the slightly lower GCC design.

RECOMMENDATIONS

On the basis of the results of the analyses, the following actions are recommended:

- To achieve a higher initial plant availability that would increase the probability of achieving 100 percent output for at least five days and 75 percent output for at least 60 days, certain design changes should be considered, as follows:

  --Tubing metallurgy of the brine side of the hydrocarbon/brine heat exchangers should be changed from carbon steel to titanium.

  --Tubing metallurgy of the hydrocarbon condensers should be changed from carbon steel to a copper-based alloy.

  --Isolation and bypass capabilities should be provided between stages of the hydrocarbon/brine heat exchangers.

  --Isolation and bypass capabilities should be provided between sets of hydrocarbon condensers/accumulators.

- Assuming that the Heber Binary Cycle Geothermal Demonstration Plant Project continues as planned, credibility of the results of these analyses can be enhanced by performing the following studies:

  --Heat balance calculations for the design should be performed to determine the contribution of each subsystem to overall plant output capacity. These results would be more accurate than the linear estimates used for plant capability in each system state. The analysis could be updated by using these data to increase the accuracy of the assessments.

  --Further investigation into the development of an expanded failure and repair data base should be considered. It probably should be based on a more detailed design. While the existing data base is reasonable and sufficient to the analysis, its accuracy could be enhanced by developing data to the levels of indenture for the components of each subsystem developed in the fault trees. While this is difficult in advanced technology designs, it can be accomplished with the cooperation of designers and equipment users and manufacturers. The development of detailed Failure Mode Effects and Criticality Analyses (FMECA) is a technique that can be employed to achieve these more detailed estimates.

  --The assessment model can and should be used to update the assessments as the Heber design evolves and also to evaluate candidate design alternatives as they are proposed. These exercises would have the effect of keeping the data base current and would provide a tool for selecting those alternatives that may be most effective.

--Since this study did not address scenarios for preventive mainte-
nance and the impact of maintenance and logistics support on plant
operations, these alternatives should be considered to add credi-
bility to the assessment.

--Consideration should be given to applying this analysis method-
ology to other geothermal plant designs and to establishing an
overall geothermal component failure and repair data base that
can support such analysis efforts in the future.

These recommendations do not take into account the effect of capital investment costs
but are limited to reliability and availability considerations only.

Appendix A

FAULT TREES

Figures A-1 through A-7 are graphic representations of the fault trees developed
for each independent subsystem (ISS) in the Heber Geothermal Demonstration Plant
preliminary design.

```
                         ┌─────────────────┐
                         │    One Heat     │
                         │ Exchanger Stage │
                         │      Fails      │
                         └─────────────────┘
```
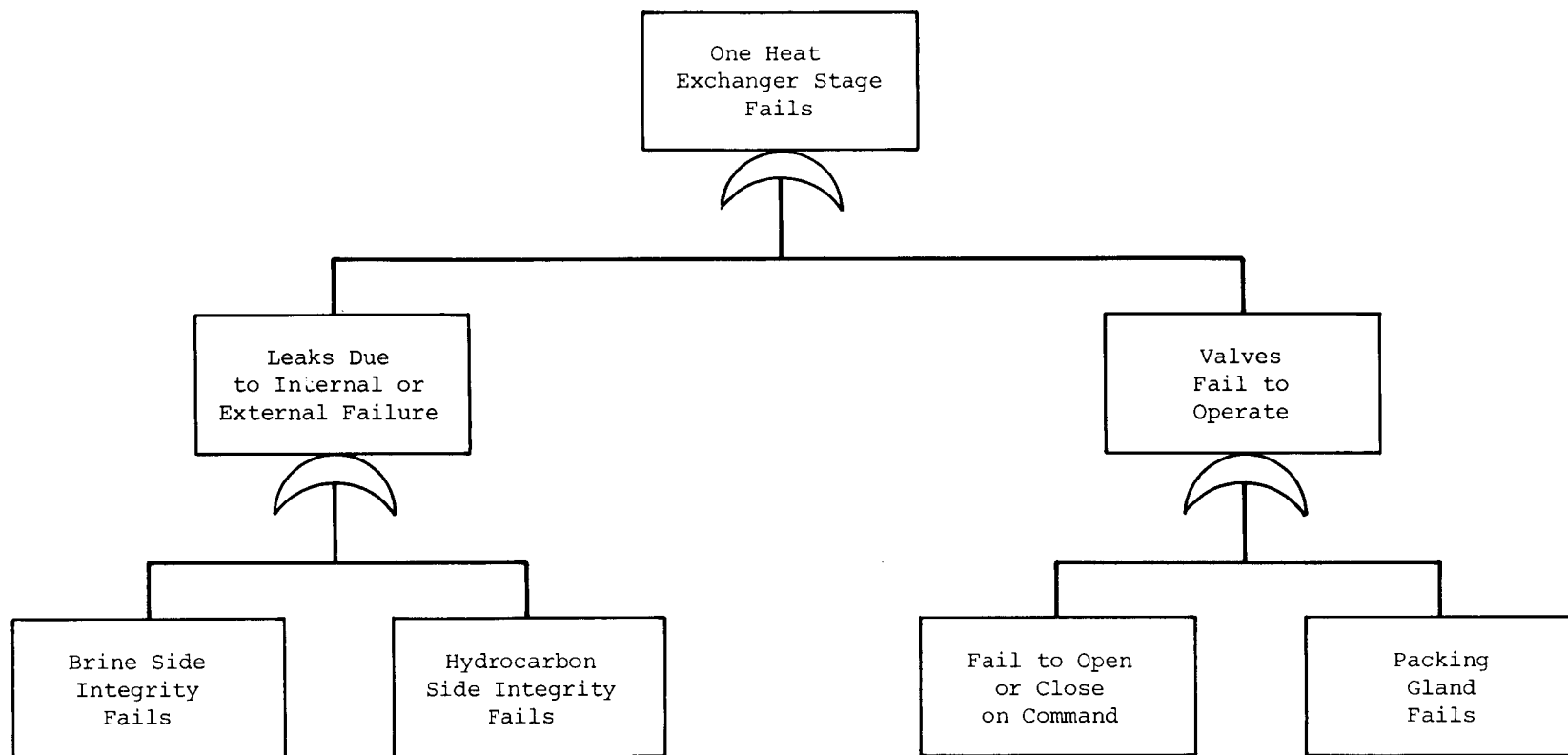
Figure A-1. Fault Tree: ISS1 - Brine/Hydrocarbon Heat Exchangers

Boxes:
- One Heat Exchanger Stage Fails
- Leaks Due to Internal or External Failure
- Valves Fail to Operate
- Brine Side Integrity Fails
- Hydrocarbon Side Integrity Fails
- Fail to Open or Close on Command
- Packing Gland Fails
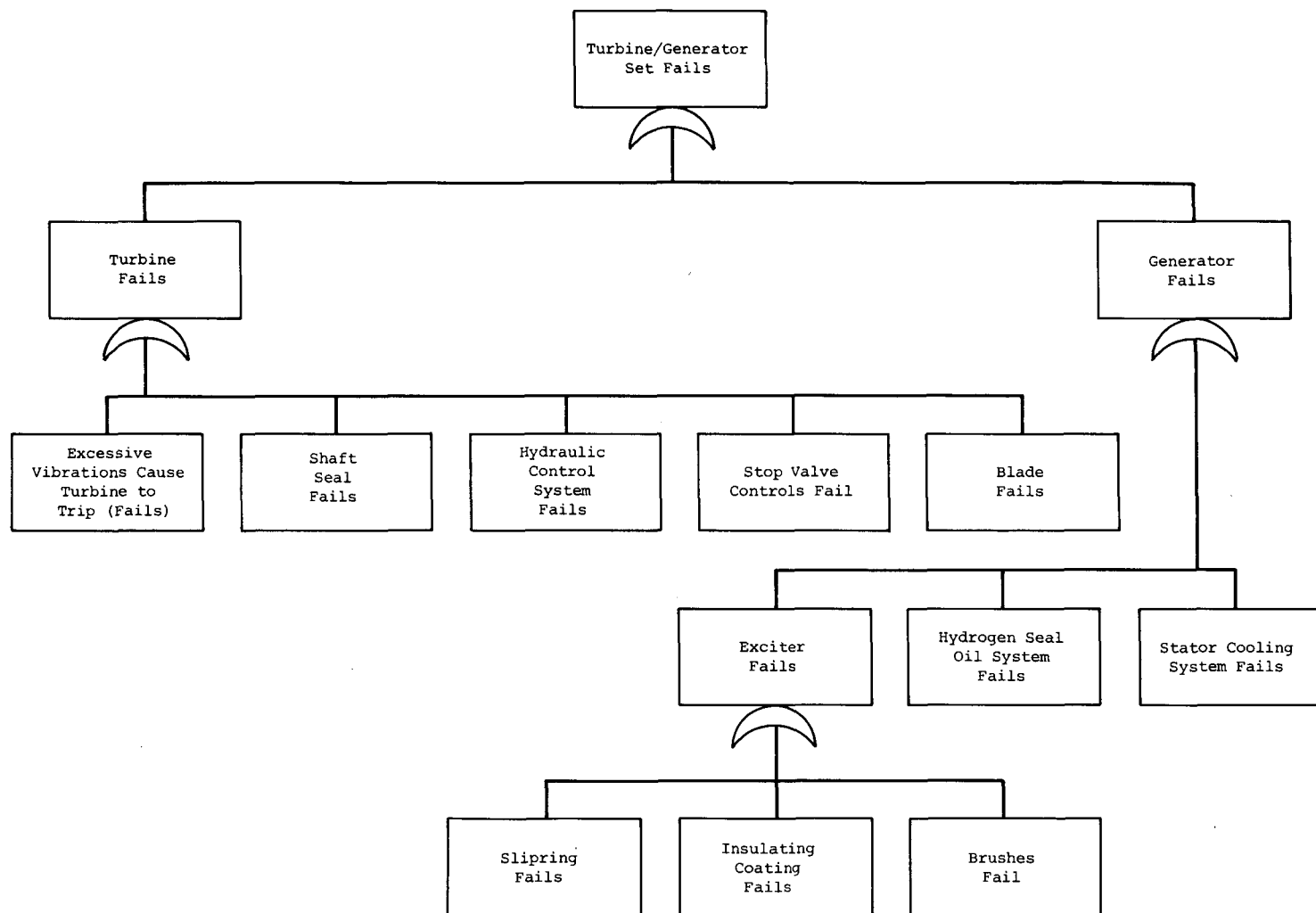
Figure A-2. Fault Tree: ISS2 - ISS2 Turbine/Generator

```
                        ┌─────────────┐
                        │  Condenser/ │
                        │ Accumulator │
                        │  Set Fails  │
                        └─────────────┘
```
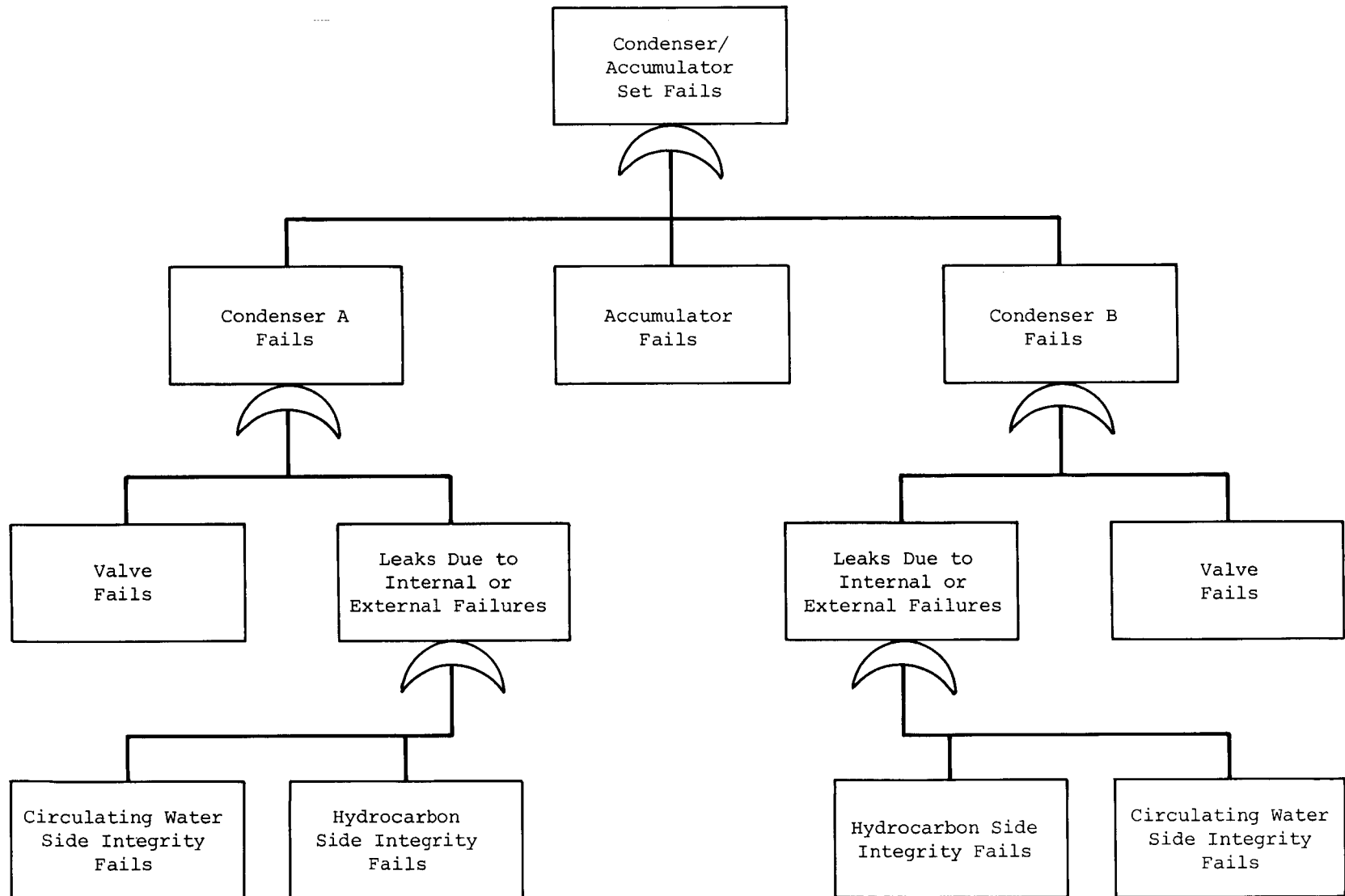
Figure A-3. Fault Tree: ISS3 - Hydrocarbon Condenser/Accumulator

Hydrocarbon
Circulation
Pumps Fail

Motor
Fails

Pump
Fails

Electric
Contacts
Fail

Power
Cable
Fails

Motor Shaft
Bearings
Fail

Valve
Packing
Fails

Pump
Bearing
Fails

Impeller
Fails

Lube Oil
System
Fails

Bearing
Cooling Water
System Fails

Shaft
Fails

Impeller
Seizes
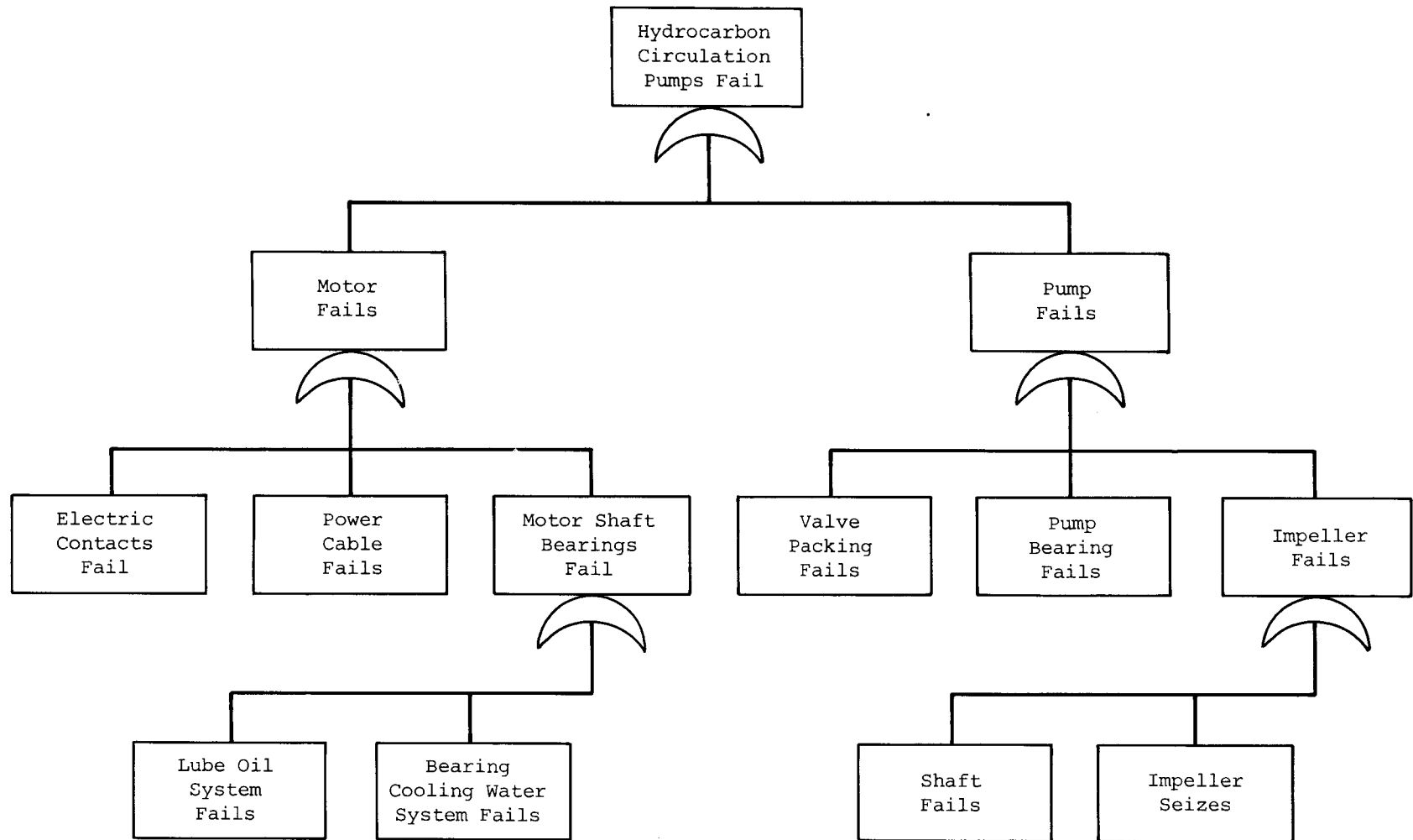
Figure A-4. Fault Tree: ISS4 - Hydrocarbon Circulation Pumps

```
                          ┌──────────────┐
                          │Cooling Tower │
                          │ Fan Module   │
                          │    Fails     │
                          └──────────────┘
```
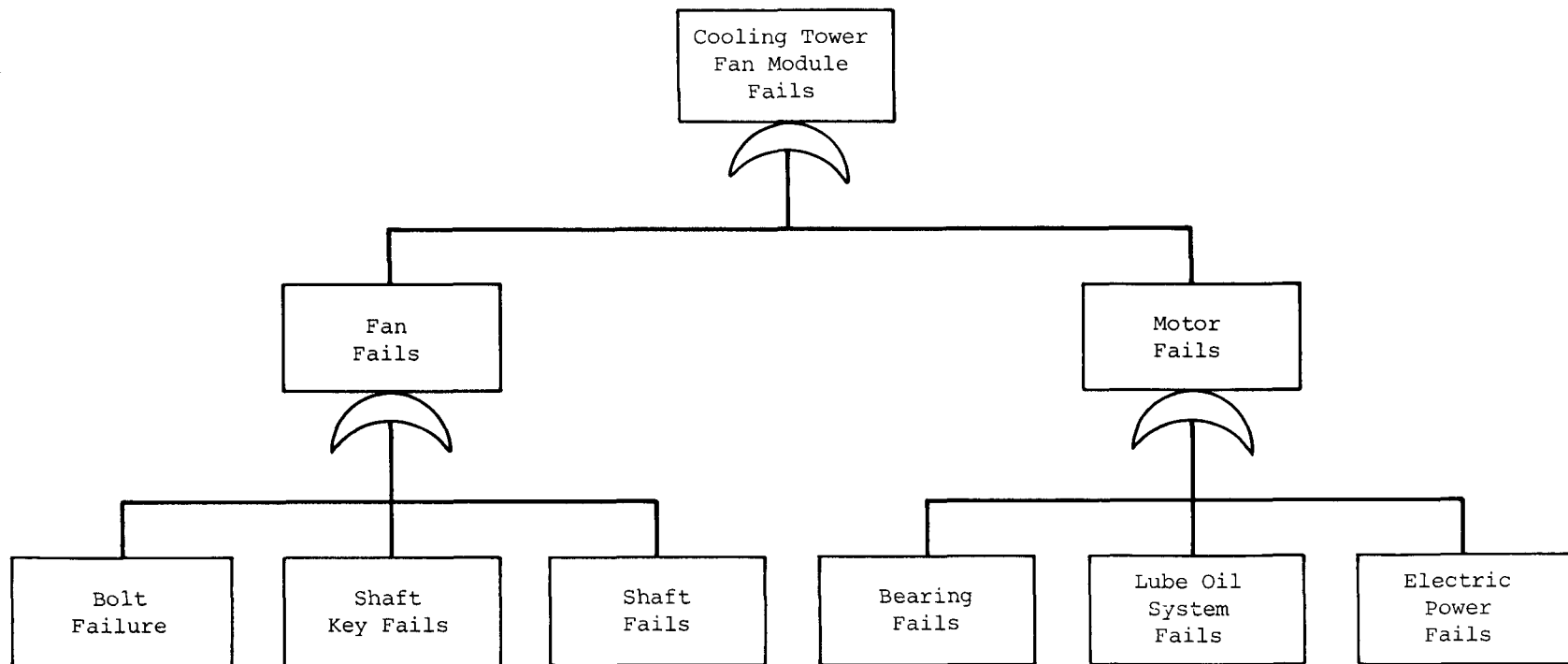
Figure A-5.   Fault Tree: ISS5 - Cooling Tower Fan Modules
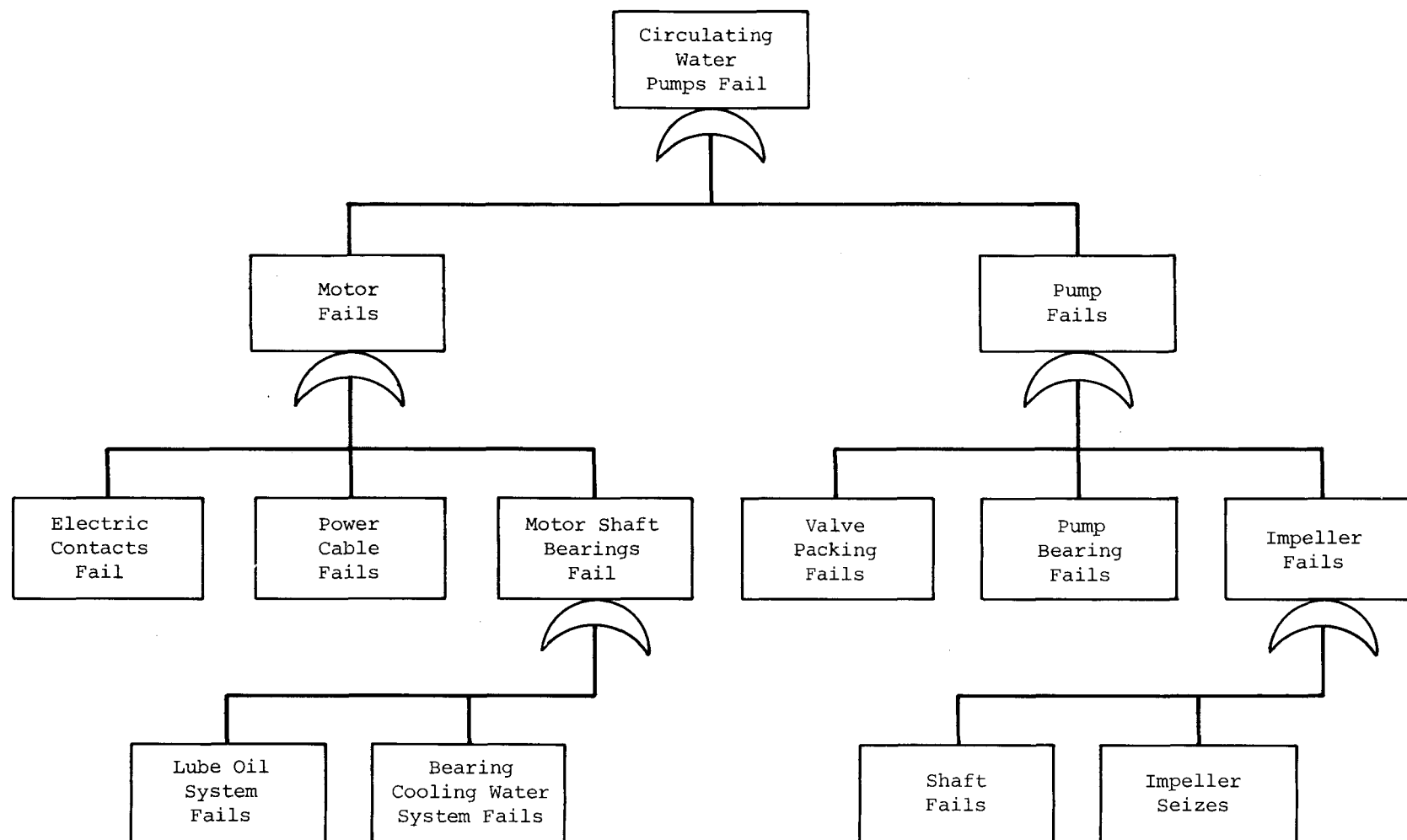
Figure A-6. Fault Tree: ISS6 – Circulating Water Pumps

```
+---------------------+
|       Brine         |
|    Reinjection      |
|      Booster        |
|    Pump Fails       |
+---------------------+
```

Figure A-7. Fault Tree: ISS7 - Brine
Reinjection Booster Pump

Appendix B

HEBER COMPONENT DATA SOURCES

Table B-1 lists the sources who provided data for each of the ISSs, including their company affiliation, location, and the type of information provided.

Table B-1

HEBER COMPONENT DATA SOURCES

ISS	Component or ISS Name	Industry and Company	Location	Type of Information Supplied
1	Heat Exchanger Trains	Petroleum--Chevron Company	Heber and Maly were test sites	Expert opinion only.
		Bromine Extraction Industry--Velsicol Great Lakes Chemical Company	El Dorado, Arkansas	Performance statistics on equivalent units and expert opinion.
2	Turbine/Generator Set Turbine	Heavy Equipment Manufacturer-- Elliot Company	Jeanette, Pennsylvania	Performance statistics on smaller units, and expert opinion and design data.
		Magma Paver		Expert opinion only.
		Utility Associations--NERC	Princeton, New Jersey	Published data.
		EEI	Washington, D.C.	Published data.
3	Hydrocarbon Condensers and Accumulators	Petroleum--Chevron Company	San Francisco, California	Expert opinion only.
		--Sun Oil Company	Philadelphia, Pennsylvania	Expert opinion only.
			Marcus Hook, Pennsylvania	Expert opinion only.
4	Hydrocarbon Circulation Pumps	See ISS3		Expert opinion only.
5	Cooling Tower Fan Modules	Utility--Carolina Power and Light Company	Roxboro and Cape Fear Stations and Raleigh Offices	Performance data.
		Potomac Electric Power	Benning Road Station Washington, D.C.	Performance data.
		Ecodyne	Philadelphia, Pennsylvania	Expert opinion and design data.
6	Circulating Water Pumps	See ISS5		Performance data.
7	Brine Reinjection Booster Pump	Bromine Extraction Industry (See ISS1)		Expert opinion based on similar units.
Plant	General Systems	EPRI	Palo Alto, California	Design and operating data.
Plant	Pilot Binary Plant	Arkansas Power & Light Company	El Dorado, Arkansas	Design and operating information.
Plant	General Design and Heat Balance	EPRI	Palo Alto, California	Design and operating information.
		The Ben Holt Company	Pasadena, California	Design data and expert estimates.

Appendix C

HEBER FLOW CHART AND PROGRAM LISTING

This appendix presents the flow chart of the Heber analysis program (Figure C-1), accompanied by detailed notes explaining the program logic. In addition, a list of variables used in the program (Table C-1) and a computer program listing (Figure C-2) are also provided.

Lines 00100 through 00280	Initialize program • Input dimensions • Identify variables		

Lines 00100
through 00280

- Initialize program
- Input dimensions
- Identify variables

Lines 00290
through 00470

Input iteration time
length, number of
iterations, whether
availability or
reliability run,
and exit value

Lines 00480
through 00540

Redo program
parameter values

Lines 00550
through 00650

Calculate subsystem
component reliability
and maintainability

Lines 00660
through 00720

Set to zero STM(K,I,J),
the subsystem substate
transition matrices

Lines 00730
through 01010
See Note 1

Calculate STM(K,I,J),
the subsystem substate
transition matrices

Lines 01020
through 01070
See Note 2

Initialize subsystem
substate availability
vectors SA(K,I)

Lines 01080
and 01090

Print run
result heading

Start iteration
process using keyboard
input NOINT on DO-Loop

Line 01100

For each iteration,
update each subsystem
substate availability
vector, SA(K,I)

Lines 01110
through 01260
See Note 3

For each iteration,
update subsystem
state availability
vector

Lines 01270
through 01410
See Note 4

For each iteration,
update system
availability vector

Lines 01420
through 01480
See Note 5

For each iteration,
update expected system
effectiveness

Lines 01490
through 01530
See Note 6

Test to
stop execution

Lines 01540
through 01580
See Note 7

Print final
subsystem state
availability vectors

Lines 01590
through 01640

Program
termination

Lines 01650
through 01670

Figure C-1. Heber Flow Chart

Notes to Heber Flow Chart

Note 1:

Each subsystem group can be in 0,1,...,NIS(K) + 1 substates, where NIS(K) is the
number of subsystems in subsystem group K. For example, ISS1 has two subsystems,
hence NIS(1)=2. Substate 1 is 0 down, substate 2 is one down, and substate 3 is
two, or all, down. It is assumed that in the iteration interval no more than one
event will occur, i.e., two or more subsystems cannot fail or be repaired; if one
fails, then another cannot be repaired, or if one is repaired, another cannot fail.
The possible paths are illustrated in the following chart:

Subsystem Group K(NIS(K) = 5		
Number Down	Substate	
	I^{th} Iteration	(I+1)st Iteration
0	1	1
1	2	2
2	3	3
3	4	4
4	5	5
5	6	6
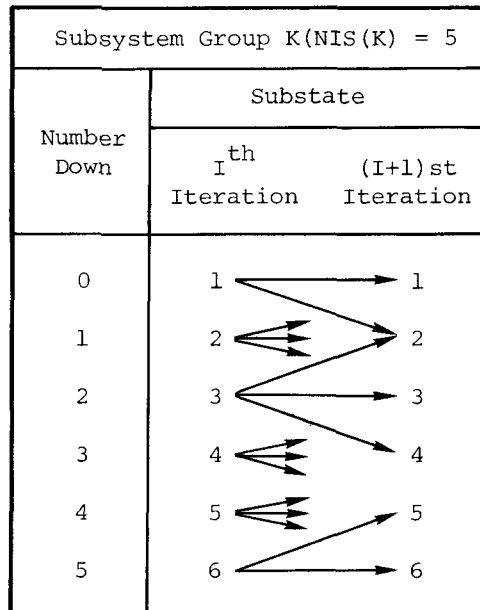
Lines 00860 and 00870 calculate the transition probabilities from substate 1 to the
two permitted substates, substates 1 and 2. To illustrate, to move from substate 1
to substate 1, none of NIS(K) must fail, thus

$$STM(K,1,1) = R(K)^{NIS(K)}$$

To move from substate 1 to substate 2, one of NIS(K) can fail, but no others; thus

$$\text{STM}(K,1,2) = (\text{NISK}[K]) \times \text{RB}(K) \times \text{R}(K)^{\text{NIS}(K)-1}$$

Lines 00790 through 00810 calculate the remaining transition probabilities. For example, line 00790 calculates the transition probability from substate I to I-1, i.e., I-1 down to I-2 down. The variable I4 in the program, equal to I-1, is the number of unavailable (or down) subsystems. It is used as the calculation variable. To move from I4 down to I4-1 down, none of the NIS(K)-I4 still up can fail, one of the I4 down can be repaired, and the remaining I4-1 must remain down, thus

$$\text{STM}(K,I,I-1) = \text{I4} \times \text{M}(K) \times \text{R}(K)^{(\text{NIS}(K)-\text{I4})} \times \text{MB}(K)^{(\text{I4}-1)}$$

A similar logic governs the remaining expressions.

The allowed transitions do not cover all of the theoretical possibilities, because the transition matrix rows do not sum to 1.0. Lines 00900 through 01010 sum the rows and divide each row element by the normalizing sum. In this way the matrix row sums are set to 1.0.

The following charts present for each ISS the normalized transition matrices calculated by the program for typical input MTBFs and MTTRs.

ISS1			
State	Probability of Transitioning from State to State		
	1	2	3
1	.987987	.012013	0
2	.068236	.926134	.005630
3	0	.128431	.871569

ISS2		
State	Probability of Transitioning from State to State	
	1	2
1	.999277	.000723
2	.038358	.961642

ISS3					
State	Probability of Transitioning from State to State				
	1	2	3	4	5
1	.997499	.002501	0	0	0
2	.037231	.960962	.001807	0	0
3	0	.071831	.927007	.001162	0
4	0	0	.104070	.895369	.000561
5	0	0	0	.134180	.865820

ISS4							
State	Probability of Transitioning from State to State						
	1	2	3	4	5	6	7
1	.989185	.010815	0	0	0	0	0
2	.073119	.918513	.008368	0	0	0	0
3	0	.136487	.857265	.006248	0	0	0
4	0	0	.240853	.756391	.002756	0	0
5	0	0	0	.284337	.714361	.001302	0
6	0	0	0	0	.284337	.714361	.001302
7	0	0	0	0	0	.323243	.676757

	ISS5							
State	Probability of Transitioning from State to State							
	1	2	3	4	5	6	7	8
1	.988149	.011851	0	0	0	0	0	0
2	.016603	.973390	.010007	0	0	0	0	0
3	0	.032718	.959066	.008216	0	0	0	0
4	0	0	.048365	.945158	.007477	0	0	0
5	0	0	0	.063565	.931646	.004789	0	0
6	0	0	0	0	.078336	.918516	.003148	0
7	0	0	0	0	0	.092697	.905751	.001552
8	0	0	0	0	0	0	.106664	.893356

	ISS6			
State	Probability of Transitioning from State to State			
	1	2	3	4
1	.999829	.000171	0	0
2	.190848	.809060	.000092	0
3	0	.320536	.679425	.000039
4	0	0	.414405	.585595

	ISS7		
State	Probability of Transitioning from State to State		
	1	2	3
1	.997580	.002420	0
2	.220990	.778066	.000944
3	0	.362266	.637734

<u>Note 2:</u>

This section initializes the ISS substate availability vectors. For example, ISS5
has seven subsystems; thus it has eight substates. It is assumed that none of
these subsystems are down prior to the first iteration, thus

$$SA(7,1) = 1.0$$

$$SA(7,1) = 0.0 \text{ for I-2 to 8}$$

(See Note 3)

<u>Note 3:</u>

If SA(K,I) is the value of the K subsystem substate availability vector on the
I^{th} iteration, its value on the next iteration is generated by this section. With
appropriate program DO LOOPS, the following vector $\times$ matrix multiplication is
executed for each ISS:

Iteration	
For J	For J+1
$SA_J(K,J)$ $=$	$SA_{J+1}(K,J) \times STM(K,I,J)$

The row vector SA(K,J) is multiplied element-by-element by the column elements of
STM(K,I,J), and the element products are summed to produce the elements of the
next value of SA(K,J).

<u>Note 4:</u>

The system state matrix identifies for each subsystem group the number of subsystems
down in each system state. Some states specify an integer, e.g., 0, 1, up to
NIS(K). Others specify that the state is defined by some number less than some
integer, e.g., <6, which means that the state exists if 0, 1, 2, 3, 4, or 5 sub-
systems are down. The system state matrix S(J,K) (J = 1,25, K = 1,7) shows a
single integer value as positive numbers and multiple integer values as negative
numbers. Thus, if S(2,3) = 2 (system state 2, subsystem 3), it means exactly two
subsystems of subsystem group 3 are down. If S(2,4) = -3, it means that zero, one,
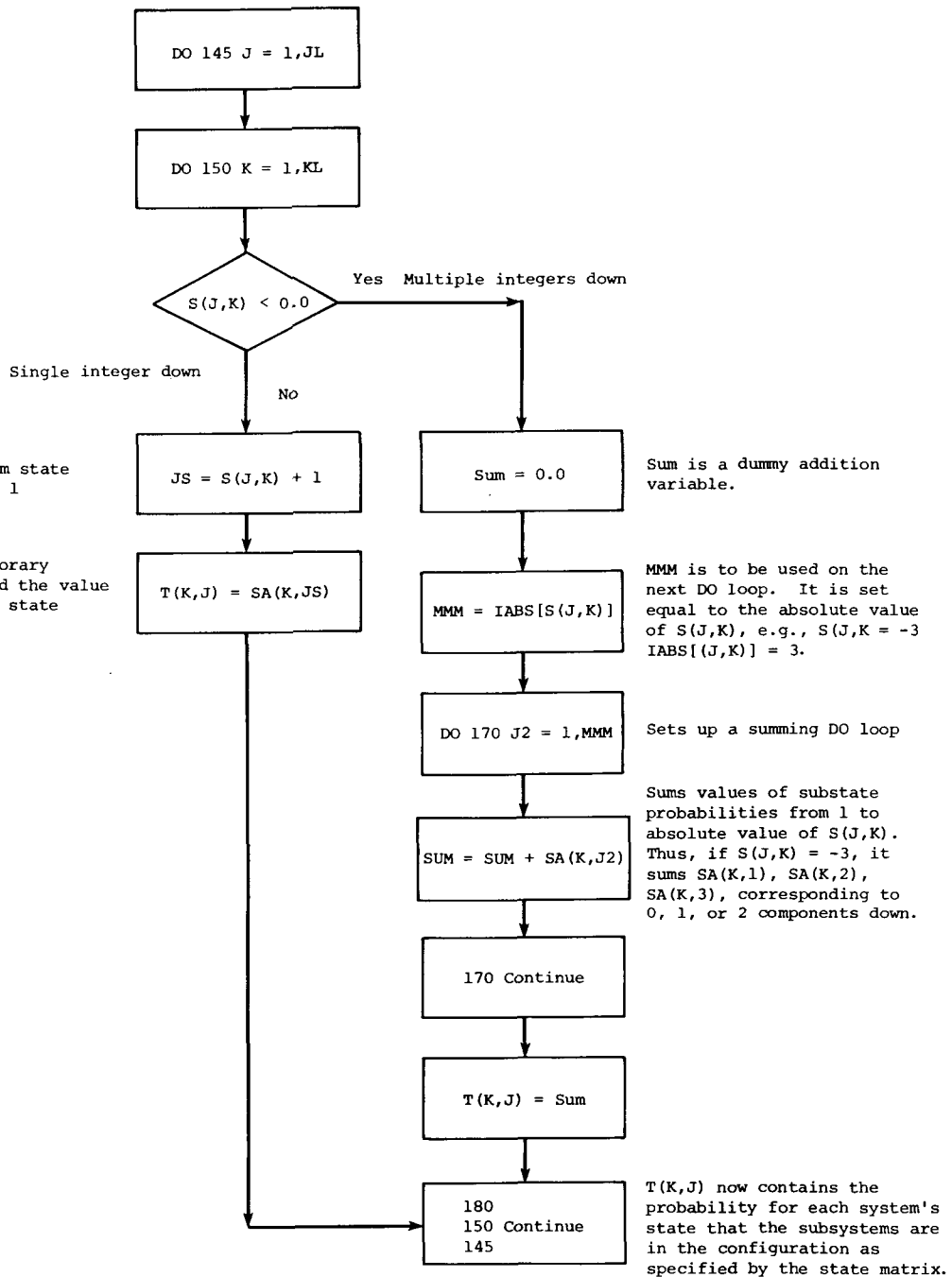or two subsystems of ISS4 are down.

The IF statement at line 01290 tests which condition exists. The following flow
diagram illustrates the logic of lines 01270 through 10410:

(JL = 25)

DO 145 J = 1,JL

(KL = 7)

DO 150 K = 1,KL

S(J,K) < 0.0

Yes   Multiple integers down

Single integer down

No

Defines subsystem state
as number down + 1

JS = S(J,K) + 1

Sum = 0.0

Sum is a dummy addition
variable.

T(K,J) is a temporary
variable assigned the value
of the subsystem state
availability.

T(K,J) = SA(K,JS)

MMM = IABS[S(J,K)]

MMM is to be used on the
next DO loop. It is set
equal to the absolute value
of S(J,K), e.g., S(J,K = -3
IABS[(J,K)] = 3.

DO 170 J2 = 1,MMM

Sets up a summing DO loop

SUM = SUM + SA(K,J2)

Sums values of substate
probabilities from 1 to
absolute value of S(J,K).
Thus, if S(J,K) = -3, it
sums SA(K,1), SA(K,2),
SA(K,3), corresponding to
0, 1, or 2 components down.

170 Continue

T(K,J) = Sum

180
150 Continue
145

T(K,J) now contains the
probability for each system's
state that the subsystems are
in the configuration as
specified by the state matrix.

Note 5:

To reiterate, the T(K,I) calculated above contains, for each system state, the probability that each ISS will be in the substate specified by the state matrix. To transform these probabilities into a system state availability, the product is taken of all substate probabilities in a state definition. Thus, if AV(I) is the system state availability, then

$$AV(I) = \prod_{K=1}^{7} T(K,I)$$

This product is formed in program lines 01420 through 01480.

Note 6:

The AV(I), I = 1,25, are calculated at each iteration. To obtain the expected system effectiveness for each iteration, the vector scalar product of AV and C is calculated

$$EFF = AV \times C = \sum_{J=1}^{25} AV(I) \times C(I)$$

This operation is performed in program lines 01490 through 01580.

Note 7:

There are two ways to stop program iteration. One way is to allow the program to stop after the keyboard-entered run length, NOINT, is encountered at line 01580. The other is to allow the program to stop when the current value of expected effectiveness differs from the last by less than the keyboard-entered variable, PCNTC. Lines 01540 through 01580 execute this option. (The idea is to terminate a run if the values of effectiveness have ceased to change to a significant degree.)

Table C-1

PROGRAM VARIABLES

Variable	Characteristic	Description
AV	Real,Vector (25)	System state availability
C	Real,Vector (25)	System state effectiveness
DELT	Real	Iteration time interval
EFF	Real	System effectiveness calculated at each iteration, EFF=AVC
EFFL	Real	System effectiveness calculated at each iteration, EFF=AVC
I,IL,IL1,I4	Integers	Dummy variables
J,JL,JS,J2	Integers	Dummy variables
K,KL,KL1,K0	Integers	Dummy variables
M,MB	Real,Vector (7)	Maintainability and nonmaintainability of each subsystem
MMM	Dummy	
MTBF,MTTR	Real,Vector (7)	Mean time between failures and mean time to repair for each subsystem
NIS	Integer (7)	Number of components in each subsystem
NOINT	Integer	Keyboard input; the number of iterations desired for the run
NRFLG	Integer	Flag used by program to distinguish between reliability and availability runs
PCNTC	Real	Keyboard input used by program to terminate a run when the percentage change in effectiveness falls below this amount
R,RB	Real,Vector (7)	Subsystem reliability and unreliability
S	Real,Matrix (25,7)	System state matrix
SA	Real,Matrix (7,8)	Subsystem state availabilities
STM	Real,Matrix (7,8,8)	Subsystem transition matrices
SUM	Dummy	
T	Real,Matrix (7,25)	For each subsystem, T is the probability that it will be in each of the 25 states; used to calculate system-state probabilities
TEST	Dummy	
TV	Dummy	Used in the transformation of T and AV

```
00100 PROGRAM HEBER(INPUT,OUTPUT,TAPE1,TAPE3,TAPE6=OUTPUT,TAPE5=INPUT)
00110 REAL MTBF(7),MTTR(7),M(7),MB(7)
00120 REAL PCNTC
00130 DIMENSION AV(25),T(7,25),NIS(7),R(7),RB(7),STM(7,8,8),SA(7,8)
00140 DIMENSION C(25)
00150 DIMENSION TSA(7,8)
00160 INTEGER S(25,7)
00170 DATA MTBF/1979.8,16594.6,19147.0,6591.6,7010.0,210900.0,9900.0/
00180 DATA MTTR/168.8,306.8,315.69,162.96,709.5,56.66,48.0/
00190 DATA NIS/2,1,4,6,7,3,2/
00200 DATA S/7*0,1,10*-2,2,6*-2,18*0,-2,1,5*0,3*0,1,4*-2,
00210+2,6*-3,3,2*-4,2*-5,4,4*-4,
00220+2*0,1,2*-2,2,3*-3,3,3*-4,4,2*-5,5,-6,3*-7,6,3*-6,
00230+0,1,2*-2,2,-3,3,5*-4,
00240+4,-5,5,2*-6,6,4*-8,7,2*-7,10*-2,2,7*-3,5*-4,3,
00250+-3,11*0,1,6*-2,6*-3,2/
00260 DATA C/1.0,.86,.83,.75,.72,.67,.58,5*.5,.43,.33,.29,
00270+.25,.17,.15,7*0.0/
00280 NRFLG=0
00290 WRITE(6,7)
00300 7 FORMAT(1H ,38H INPUT ITERATION TIME LENGTH IN HOURS.)
00310 READ(5,*) DELT
00320 WRITE(6,8)
00330 8 FORMAT(1H ,28H INPUT NUMBER OF ITERATIONS.)
00340 READ(5,*) NOINT
00350 613 WRITE(6,9)
00360 9 FORMAT(1H ,40HIS THIS A REL OR AVAIL RUN? TYPE 0 OR 1.)
00370 READ (5,*) L1
00380 IF(L1.EQ.0) GOTO 614
00390 IF(L1.EQ.1) GOTO 616
00400 WRITE(6,11)
00410 11 FORMAT(1H ,41HYOU HAVE ANSWERED INCORRECTLY. TRY AGAIN.)
00420 GOTO 613
00430 614 NRFLG=1
00440 616 CONTINUE
00450 WRITE(6,1500)
00460 1500 FORMAT(1H ,12HENTER MARG.%)
00470 READ*,PCNTC
00480 JL=25
00490 JL=25
00500 IL=25
00510 IL1=26
00520 KL=7
00530 KL1=8
00540 EFFL=.0001
00550 DO 1000 K=1,KL
00560 R(K)=EXP(-DELT/MTBF(K))
00570 RB(K)=1-R(K)
00580 IF(NRFLG.EQ.1) GOTO 617
00590 M(K)=1-EXP(-DELT/MTTR(K))
00600 MB(K)=1-M(K)
00610 GOTO 618
```

(continued)

Figure C-2.   Heber Program Listing

```
00620 617 M(K)=0.0
00630 MB(K)=1.0
00640 618 CONTINUE
00650 1000 CONTINUE
00660 DO 10 K=1,KL
00670 DO 20 J=1,KL1
00680 DO 30 I=1,KL1
00690 STM(K,I,J)=0.0
00700 30 CONTINUE
00710 20 CONTINUE
00720 10 CONTINUE
00730 DO 40 K=1,KL
00740 KL1=NIS(K)+1
00750 DO 50 I=1,KL1
00760 I4=I-1
00770 IF(I.EQ.1)GOTO 60
00780 IF(I.EQ.KL1) GOTO 70
00790 STM(K,I,I-1)=I4*R(K)**(NIS(K)-I4)*MB(K)**(I4-1)*M(K)
00800 STM(K,I,I)=R(K)**(NIS(K)-I4)*MB(K)**I4
00810 STM(K,I,I+1)=(NIS(K)-I4)*R(K)**(NIS(K)-I4-1)*MB(K)**I4*RB(K)
00820 GOTO 50
00830 70 STM(K,I,I-1)=R(K)**(NIS(K)-I4)*I4*MB(K)**(I4-1)*M(K)
00840 STM(K,I,I)=R(K)**(NIS(K)-I4)*MB(K)**I4
00850 GOTO 50
00860 60 STM(K,1,1)=R(K)**NIS(K)
00870 STM(K,1,2)=R(K)**(NIS(K)-1)*RB(K)*NIS(K)
00880 50 CONTINUE
00890 40 CONTINUE
00900 DO 80 K=1,KL
00910 KL1=NIS(K)+1
00920 DO 90 I=1,KL1
00930 SUM=0.0
00940 DO 100 J=1,KL1
00950 SUM=SUM+STM(K,I,J)
00960 100 CONTINUE
00970 DO 110 JS=1,KL1
00980 STM(K,I,JS)=STM(K,I,JS)/SUM
00990 110 CONTINUE
01000 90 CONTINUE
01010 80 CONTINUE
01020 DO 120 K=1,7
01030 SA(K,1)=1.0
01040 DO 125 J=2,8
01050 SA(K,J)=0.0
01060 125 CONTINUE
01070 120 CONTINUE
01080 WRITE(6,600)
01090 600 FORMAT(1H ,5HITER#,3X,4HEFF=,F9.7)
01100 DO 200 KO=1,NOINT
01110 DO 130 K=1,7
01120 KL1=NIS(K)+1
01130 DO 135 I=1,KL1
01140 SUM=0.0
```

(continued)

Figure C-2.   (continued)

```
01150 DO 140 J=1,KL1
01160 SUM=SUM+SA(K,J)*STM(K,J,I)
01170 140 CONTINUE
01180 TSA(K,I)=SUM
01190 135 CONTINUE
01200 130 CONTINUE
01210 DO 900 K=1,7
01220 KL1=NIS(K)+1
01230 DO 910 I=1,KL1
01240 SA(K,I)=TSA(K,I)
01250 910 CONTINUE
01260 900 CONTINUE
01270 DO 145 J=1,JL
01280 DO 150 K=1,KL
01290 IF(S(J,K).LT.0) GOTO 160
01300 JS=S(J,K)+1
01310 T(K,J)=SA(K,JS)
01320 GOTO 180
01330 160 SUM=0.0
01340 MMM=IABS(S(J,K))
01350 DO 170 J2=1,MMM
01360 SUM=SUM+SA(K,J2)
01370 170 CONTINUE
01380 T(K,J)=SUM
01390 180 CONTINUE
01400 150 CONTINUE
01410 145 CONTINUE
01420 DO 500 I=1,25
01430 TV=1.0
01440 DO 510 K=1,7
01450 TV=TV*T(K,I)
01460 510 CONTINUE
01470 AV(I)=TV
01480 500 CONTINUE
01490 SUM=0.0
01500 DO 220 J=1,25
01510 SUM=SUM+AV(J)*C(J)
01520 220 CONTINUE
01530 EFF=SUM
01540 TEST=ABS((EFFL-EFF)/EFFL)
01550 WRITE(6,632)KO,SUM
01560 632 FORMAT(1H ,I4,2X,F9.7)
01570 IF(TEST.LE.PCNTC)GOTO 310
01580 IF(KO.LT.NOINT) GOTO 200
01590 DO 1100 K=1,7
01600 DO 1110 J=1,8
01605 IF(SA(K,J).EQ.0.0)GOTO 1110
01610 WRITE(6,1120)K,J,SA(K,J)
01620 1120 FORMAT(1H ,I1,X,I1,X,F9.7)
01630 1110 CONTINUE
01640 1100 CONTINUE
01650 200 CONTINUE
01660 310 STOP
01670 END
/
 L
```

Figure C-2. (continued)

Appendix D

COMPONENT-RANKING EXPRESSIONS

This appendix presents the mathematical formulations employed in obtaining scores for the component-ranking criteria used in the analysis. These criteria are representative of power lost, availability, failure rate, and mean time to restore.

$$\text{Power Lost} = \lim_{A_{ij} \to 1} \left(E_{ss} \right) - E_{ss}$$

$$\text{Availability} = \frac{\delta E_{ss}}{\delta A_{ij}} = \frac{\delta E_{ss}}{\delta A_i} \frac{\delta A_i}{\delta A_{ij}}$$

$$\text{Failure Rate} = \frac{\delta E_{ss}}{\delta \lambda_{ij}} = \frac{\delta E_{ss}}{\delta A_i} \frac{\delta A_i}{\delta A_{ij}} \frac{\delta A_{ij}}{\delta \lambda_{ij}} = \frac{\delta E_{ss}}{\delta A_i} A_i A_{ij} \tau_{ij}$$

$$\text{Mean Time to Restore} = \frac{\delta E_{ss}}{\delta A_i} \frac{\delta A_i}{\delta A_{ij}} \frac{\delta A_{ij}}{\delta \lambda_{ij}} = \frac{\delta E_{ss}}{\delta A_i} A_i A_{ij} \lambda_{ij}$$

where

E_{ss} = the steady-state effectiveness measure of the plant

$\dfrac{\delta E_{ss}}{\delta A_i}$ = the change in the steady-state effectiveness resulting from a change in the ith subsystem availability (A_i) obtained from the sensitivity exercises of the model

A_{ij} = the availability of the jth component in the ith subsystem
$= \dfrac{1}{\lambda_{ij} \tau_{ij} + 1}$

λ_{ij} = the jth component in the ith subsystem failure rate

τ_{ij} = the jth component in the ith subsystem mean time to restore